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(54) Title: HIGH EFFICIENCY, HIGH PERFORMANCE COMMUNICATIONS SYSTEM EMPLOYING MULTI-CARRIER MODULATION

(57) Abstract: Transmitter and receiver units for use in a communications system and configurable to provide antenna, frequency, or temporal diversity, or a combination thereof, for transmitted signals. The transmitter unit includes a system data processor, one or more modulators, and one or more antennas. The system data processor receives and partitions an input data stream into a number of channel data streams and further processes the channel data streams to generate one or more modulation symbol vector streams. Each modulation symbol vector stream includes a sequence of modulation symbol vectors representative of data in one or more channel data streams. Each modulator receives and modulates a respective modulation symbol vector stream to provide an RF modulated signal, and each antenna receives and transmits a respective RF modulated signal. Each modulator may include an inverse (fast) Fourier transform (IFFT) and a cyclic prefix generator. The IFFT generates time-domain representations of the modulation symbol vectors, and the cyclic prefix generator repeats a portion of the time-domain representation of each modulation symbol vector. The channel data streams are modulated using multi-carrier modulation, e.g., OFDM modulation. Time division multiplexing (TDM) may also be used to increase flexibility.

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HIGH EFFICIENCY, HIGH PERFORMANCE COMMUNICATIONS SYSTEM EMPLOYING MULTI-CARRIER MODULATION

5 BACKGROUND OF THE INVENTION

I. Field of the Invention

10 The present invention relates to data communication. More particularly, the present invention relates to a novel and improved communications system employing multi-carrier modulation and having high efficiency, improved performance, and enhanced flexibility.

15 II. Description of the Related Art

A modern day communications system is required to support a variety of applications. One such communications system is a code division multiple access (CDMA) system that conforms to the "TIA/EIA/IS-95 Mobile Station-Base Station Compatibility Standard for Dual-Mode Wideband Spread Spectrum Cellular System," hereinafter referred to as the IS-95 standard. The CDMA system supports voice and data communication between users over a terrestrial link. The use of CDMA techniques in a multiple access communication system is disclosed in U.S. Patent No. 4,901,307, entitled "SPREAD SPECTRUM MULTIPLE ACCESS COMMUNICATION SYSTEM USING SATELLITE OR TERRESTRIAL REPEATERS," and U.S. Patent No. 5,103,459, entitled "SYSTEM AND METHOD FOR GENERATING WAVEFORMS IN A CDMA CELLULAR TELEPHONE SYSTEM," both assigned to the assignee of the present invention and incorporated herein by reference.

30 An IS-95 compliant CDMA system is capable of supporting voice and data services over the forward and reverse communications links. Typically, each voice call or each traffic data transmission is assigned a dedicated channel having a variable but limited data rate. In accordance with the IS-95 standard, the traffic or voice data is partitioned into code channel frames that are 20 msec in duration with data rates as high as 14.4 Kbps. The frames are then transmitted over the assigned channel. A method for transmitting traffic data in code channel frames of fixed size is described in U.S. Patent No. 5,504,773, entitled "METHOD AND APPARATUS FOR THE FORMATTING OF DATA FOR TRANSMISSION,"

assigned to the assignee of the present invention and incorporated herein by reference.

A number of significant differences exist between the characteristics and requirements of voice and data services. One such difference is the fact that voice services impose stringent and fixed delay requirements whereas data services can usually tolerate variable amounts of delay. The overall one-way delay of speech frames is typically required to be less than 100 msec. In contrast, the delay for data frames is typically a variable parameter that can be advantageously used to optimize the overall efficiency of the data communications system.

The higher tolerance to delay allows traffic data to be aggregated and transmitted in bursts, which can provide a higher level of efficiency and performance. For example, data frames may employ more efficient error correcting coding techniques requiring longer delays that cannot be tolerated by voice frames. In contrast, voice frames may be limited to the use of less efficient coding techniques having shorter delays.

Another significant difference between voice and data services is that the former typically requires a fixed and common grade of service (GOS) for all users, which is usually not required or implemented for the latter. For digital communications systems providing voice services, this typically translates into a fixed and equal transmission rate for all users and a maximum tolerable value for the error rate of speech frames. In contrast, for data services, the GOS may be different from user to user and is also typically a parameter that can be advantageously optimized to increase the overall efficiency of the system. The GOS of a data communications system is typically defined as the total delay incurred in the transfer of a particular amount of data.

Yet another significant difference between voice and data services is that the former require a reliable communications link that, in a CDMA system, is provided by soft handoff. Soft handoff results in redundant transmissions from two or more base stations to improve reliability. However, this additional reliability may not be required for data transmission because data frames received in error may be retransmitted. For data services, the transmit power needed to support soft handoff may be more efficiently used for transmitting additional data.

Because of the significant differences noted above, it is a challenge to design a communications system capable of efficiently supporting both voice and data services. The IS-95 CDMA system is designed to efficiently

transmit voice data, and is also capable of transmitting traffic data. The design of the channel structure and the data frame format pursuant to IS-95 have been optimized for voice data. A communications system based on IS-95 that is enhanced for data services is disclosed in U.S. Patent Application
5 Serial No. 08/963,386, entitled "METHOD AND APPARATUS FOR HIGH RATE PACKET DATA TRANSMISSION," filed November 3, 1997, assigned to the assignee of the present invention and incorporated herein by reference.

Given the ever-growing demand for wireless voice and data
10 communication, however a higher efficiency, higher performance wireless communications system capable of supporting voice and data services is desirable.

SUMMARY OF THE INVENTION

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The present invention is directed to a novel and improved communications system capable of providing increased spectral efficiency, improved performance, and enhanced flexibility by employing a combination of antenna, frequency, and temporal diversity. The
20 communications system can be operative to concurrently support a number of transmissions of various types (e.g., control, broadcast, voice, traffic data, and so on) that may have disparate requirements. Various aspects, features, and embodiments of the communications system are described below.

An embodiment of the invention provides a transmitter unit for use
25 in a communications system and configurable to provide antenna, frequency, or temporal diversity, or a combination thereof, for transmitted signals. The transmitter unit includes a system data processor, one or more modulators, and one or more antennas. The system data processor receives and partitions an input data stream into a number of (K) channel data
30 streams and further processes the channel data streams to generate one or more (N_T) modulation symbol vector streams. Each modulation symbol vector stream includes a sequence of modulation symbol vectors representative of data in one or more channel data streams.

Each modulator modulates a respective modulation symbol vector
35 stream to provide a modulated signal, and each antenna receives and transmits a respective modulated signal. Each modulator typically includes an inverse (fast) Fourier transform (IFFT) and a cyclic prefix generator. The IFFT generates time-domain representations of the modulation symbol

vectors, and the cyclic prefix generator repeats a portion of the time-domain representation of each modulation symbol vector.

The system data processor may include one or more channel data processors, encoders, demultiplexers, and combiners. In a specific
5 implementation, each encoder encodes a respective channel data stream to generate an encoded data stream, each channel data processor processes a respective encoded data stream to generate a stream of modulation symbols, each demultiplexer demultiplexes the stream of modulation symbols into one or more symbol sub-streams, and each combiner selectively combines
10 the symbol sub-streams to generate a modulation symbol vector stream for an associated antenna.

In accordance with an aspect of the invention, the channel data streams are modulated using multi-carrier modulation (e.g., orthogonal frequency division multiplexing (OFDM) modulation). The multi-carrier
15 modulation partitions the system operating bandwidth, W , into a number of (L) sub-bands. Each sub-band is associated with a different center frequency and corresponds to one sub-channel.

The modulation symbol vectors are generated and transmitted in a manner to provide antenna, frequency, or temporal diversity, or a
20 combination thereof. For example, the data for a particular channel data stream may be transmitted from one or more antennas, on one or more sub-bands of the system operating bandwidth, and at one or more time periods to respectively provide antenna, frequency, and temporal diversity. Various communications modes (e.g., diversity and MIMO) may be supported and
25 are described in greater detail below.

Each channel data stream, each sub-channel, each antenna, or some other unit of transmission can be modulated with a particular modulation scheme selected from a set that includes, for example, M-PSK and M-QAM. The encoding can be achieved on each channel data stream, each sub-
30 channel, and so on. Pre-conditioning of the data may also be performed at the transmitter unit using channel state information (CSI) descriptive of the characteristics of the communications links. Such CSI may include, for example, the eigenmodes corresponding to, or the C/I values for, the communications links, which are described below.

35 Time division multiplexing (TDM) may also be used to increase flexibility, especially for traffic data transmission. The channel data streams may thus be transmitted in time slots, with each time slot having a duration that is related to, for example, the length of a modulation symbol. A voice

call may be assigned a portion of the available system resources (e.g., a particular sub-channel) to minimize processing delay. Traffic data for a particular transmission may be aggregated and transmitted in one or more time slots for improved efficiency. Pilot and other types of data may also be
5 multiplexed and transmitted on selected time slots.

Another embodiment of the invention provides a receiver unit that includes, for example, at least one antenna, at least one front end processor, at least one (fast) Fourier transform (FFT), a processor, at least one demodulator, and at least one decoder. Each antenna receives one or more
10 modulated signals and provides the received signal to a respective front end processor that processes the signal to generate samples. Each FFT converts the samples from a respective front end processor into transformed representations. The transformed representations from the at least one FFT processor are then processed by the processor into one or more symbol
15 streams, with each symbol stream corresponding to a particular transmission (e.g., control, broadcast, voice, or traffic data) being processed.

Each demodulator demodulates a respective symbol stream to generate demodulated data, and each decoder decodes respective demodulated data to generate decoded data. The modulated signals are
20 generated and transmitted and/or received in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof, as described below.

Yet another embodiment of the invention provides a method for generating and transmitting one or more modulated signals. In accordance
25 with the method, an input data stream is received and partitioned into a number of channel data streams. The channel data streams are then encoded with one or more encoding schemes and modulated with one or more modulation schemes to generate modulation symbols. Symbols corresponding to the sub-channels of each antenna are then combined into
30 modulation symbol vectors, which are then provided as a modulation symbol vector stream. Again, the modulation symbol vectors are generated and transmitted in a manner to provide antenna, frequency, or temporal diversity, or a combination thereof.

35

BRIEF DESCRIPTION OF THE DRAWINGS

The features, nature, and advantages of the present invention will become more apparent from the detailed description set forth below when

taken in conjunction with the drawings in which like reference characters identify correspondingly throughout and wherein:

FIG. 1 is a diagram of a multiple-input multiple-output (MIMO) communications system;

5 FIG. 2 is a diagram that graphically illustrates a specific example of a transmission from a transmit antenna at a transmitter unit;

FIG. 3 is a block diagram of an embodiment of a data processor and a modulator of the communications system shown in FIG. 1;

10 FIGS. 4A and 4B are block diagrams of two embodiments of a channel data processor that can be used for processing one channel data stream such as control, broadcast, voice, or traffic data;

FIGS. 5A through 5C are block diagrams of an embodiment of the processing units that can be used to generate the transmit signal shown in FIG. 2;

15 FIG. 6 is a block diagram of an embodiment of a receiver unit, having ~~multiple receive antennas, which can be used to receive one or more~~ channel data streams; and

FIG. 7 shows plots that illustrate the spectral efficiency achievable with some of the operating modes of a communications system in
20 accordance with one embodiment.

DETAILED DESCRIPTION OF THE SPECIFIC EMBODIMENTS

FIG. 1 is a diagram of a multiple-input multiple-output (MIMO) communications system 100 capable of implementing some embodiments of the invention. Communications system 100 can be operative to provide a combination of antenna, frequency, and temporal diversity to increase spectral efficiency, improve performance, and enhance flexibility. Increased spectral efficiency is characterized by the ability to transmit more bits per second per Hertz (bps/Hz) when and where possible to better utilize the available system bandwidth. Techniques to obtain higher spectral efficiency are described in further detail below. Improved performance may be quantified, for example, by a lower bit-error-rate (BER) or frame-error-rate (FER) for a given link carrier-to-noise-plus-interference ratio (C/I). And
35 enhanced flexibility is characterized by the ability to accommodate multiple users having different and typically disparate requirements. These goals may be achieved, in part, by employing multi-carrier modulation, time division multiplexing (TDM), multiple transmit and/or receive antennas,

and other techniques. The features, aspects, and advantages of the invention are described in further detail below.

As shown in FIG. 1, communications system 100 includes a first system 110 in communication with a second system 120. System 110 includes a (transmit) data processor 112 that (1) receives or generates data, (2) processes the data to provide antenna, frequency, or temporal diversity, or a combination thereof, and (3) provides processed modulation symbols to a number of modulators (MOD) 114a through 114t. Each modulator 114 further processes the modulation symbols and generates an RF modulated signal suitable for transmission. The RF modulated signals from modulators 114a through 114t are then transmitted from respective antennas 116a through 116t over communications links 118 to system 120.

In the embodiment shown in FIG. 1, system 120 includes a number of receive antennas 122a through 122r that receive the transmitted signals and provide the received signals to respective demodulators (DEMOMOD) 124a through 124r. As shown in FIG. 1, each receive antenna 122 may receive signals from one or more transmit antennas 116 depending on a number of factors such as, for example, the operating mode used at system 110, the directivity of the transmit and receive antennas, the characteristics of the communications links, and others. Each demodulator 124 demodulates the respective received signal using a demodulation scheme that is complementary to the modulation scheme used at the transmitter. The demodulated symbols from demodulators 124a through 124r are then provided to a (receive) data processor 126 that further processes the symbols to provide the output data. The data processing at the transmitter and receiver units is described in further detail below.

FIG. 1 shows only the forward link transmission from system 110 to system 120. This configuration may be used for data broadcast and other one-way data transmission applications. In a bi-directional communications system, a reverse link from system 120 to system 110 is also provided, although not shown in FIG. 1 for simplicity. For the bi-directional communications system, each of systems 110 and 120 may operate as a transmitter unit or a receiver unit, or both concurrently, depending on whether data is being transmitted from, or received at, the unit.

For simplicity, communications system 100 is shown to include one transmitter unit (i.e., system 110) and one receiver unit (i.e., system 120). However, other variations and configurations of the communications system are possible. For example, in a multi-user, multiple access

communications system, a single transmitter unit may be used to concurrently transmit data to a number of receiver units. Also, in a manner similar to soft-handoff in an IS-95 CDMA system, a receiver unit may concurrently receive transmissions from a number of transmitter units.

5 The communications system of the invention may include any number of transmitter and receiver units.

Each transmitter unit may include a single transmit antenna or a number of transmit antennas, such as that shown in FIG. 1. Similarly, each receiver unit may include a single receive antenna or a number of receive

10 antennas, again such as that shown in FIG. 1. For example, the communications system may include a central system (i.e., similar to a base station in the IS-95 CDMA system) having a number of antennas that transmit data to, and receive data from, a number of remote systems (i.e., subscriber units, similar to remote stations in the CDMA system), some of

15 which may include one antenna and others of which may include multiple antennas. ~~Generally, as the number of transmit and receive antennas~~ increases, antenna diversity increases and performance improves, as described below.

As used herein, an antenna refers to a collection of one or more

20 ~~antenna elements that are distributed in space. The antenna elements may~~ be physically located at a single site or distributed over multiple sites. Antenna elements physically co-located at a single site may be operated as an antenna array (e.g., such as for a CDMA base station). An antenna network consists of a collection of antenna arrays or elements that are physically

25 separated (e.g., several CDMA base stations). An antenna array or an antenna network may be designed with the ability to form beams and to transmit multiple beams from the antenna array or network. For example, a CDMA base station may be designed with the capability to transmit up to three beams to three different sections of a coverage area (or sectors) from

30 the same antenna array. Thus, the three beams may be viewed as three transmissions from three antennas.

The communications system of the invention can be designed to provide a multi-user, multiple access communications scheme capable of supporting subscriber units having different requirements as well as

35 capabilities. The scheme allows the system's total operating bandwidth, W , (e.g., 1.2288 MHz) to be efficiently shared among different types of services that may have highly disparate data rate, delay, and quality of service (QOS) requirements.

Examples of such disparate types of services include voice services and data services. Voice services are typically characterized by a low data rate (e.g., 8 kbps to 32 kbps), short processing delay (e.g., 3 msec to 100 msec overall one-way delay), and sustained use of a communications channel for an extended period of time. The short delay requirements imposed by voice services typically require a small fraction of the system resources to be dedicated to each voice call for the duration of the call. In contrast, data services are characterized by "bursty" traffics in which variable amounts of data are sent at sporadic times. The amount of data can vary significantly from burst-to-burst and from user-to-user. For high efficiency, the communications system of the invention can be designed with the capability to allocate a portion of the available resources to voice services as required and the remaining resources to data services. In some embodiments of the invention, a fraction of the available system resources may also be dedicated for certain data services or certain types of data services.

The distribution of data rates achievable by each subscriber unit can vary widely between some minimum and maximum instantaneous values (e.g., from 200 kbps to over 20 Mbps). The achievable data rate for a particular subscriber unit at any given moment may be influenced by a number of factors such as the amount of available transmit power, the quality of the communications link (i.e., the C/I), the coding scheme, and others. The data rate requirement of each subscriber unit may also vary widely between a minimum value (e.g., 8 kbps, for a voice call) all the way up to the maximum supported instantaneous peak rate (e.g., 20 Mbps for bursty data services).

The percentage of voice and data traffic is typically a random variable that changes over time. In accordance with certain aspects of the invention, to efficiently support both types of services concurrently, the communications system of the invention is designed with the capability to dynamic allocate the available resources based on the amount of voice and data traffic. A scheme to dynamically allocate resources is described below. Another scheme to allocate resources is described in the aforementioned U.S. Patent Application Serial No. 08/963,386.

The communications system of the invention provides the above-described features and advantages, and is capable of supporting different types of services having disparate requirements. The features are achieved by employing antenna, frequency, or temporal diversity, or a combination

thereof. In some embodiments of the invention, antenna, frequency, or temporal diversity can be independently achieved and dynamically selected.

As used herein, antenna diversity refers to the transmission and/or reception of data over more than one antenna, frequency diversity refers to the transmission of data over more than one sub-band, and temporal diversity refers to the transmission of data over more than one time period. Antenna, frequency, and temporal diversity may include subcategories. For example, transmit diversity refers to the use of more than one transmit antenna in a manner to improve the reliability of the communications link, receive diversity refers to the use of more than one receive antenna in a manner to improve the reliability of the communications link, and spatial diversity refers to the use of multiple transmit and receive antennas to improve the reliability and/or increase the capacity of the communications link. Transmit and receive diversity can also be used in combination to improve the reliability of the communications link without increasing the link capacity. Various combinations of antenna, frequency, and temporal diversity can thus be achieved and are within the scope of the present invention.

Frequency diversity can be provided by use of a multi-carrier modulation scheme such as orthogonal frequency division multiplexing (OFDM), which allows for transmission of data over various sub-bands of the operating bandwidth. Temporal diversity is achieved by transmitting the data over different times, which can be more easily accomplished with the use of time-division multiplexing (TDM). These various aspects of the communications system of the invention are described in further detail below.

In accordance with an aspect of the invention, antenna diversity is achieved by employing a number of (N_T) transmit antennas at the transmitter unit or a number of (N_R) receive antennas at the receiver unit, or multiple antennas at both the transmitter and receiver units. In a terrestrial communications system (e.g., a cellular system, a broadcast system, an MMDS system, and others), an RF modulated signal from a transmitter unit may reach the receiver unit via a number of transmission paths. The characteristics of the transmission paths typically vary over time based on a number of factors. If more than one transmit or receive antenna is used, and if the transmission paths between the transmit and receive antennas are independent (i.e., uncorrelated), which is generally true to at least an extent, then the likelihood of correctly receiving the transmitted

signal increases as the number of antennas increases. Generally, as the number of transmit and receive antennas increases, diversity increases and performance improves.

In some embodiments of the invention, antenna diversity is dynamically provided based on the characteristics of the communications link to provide the required performance. For example, higher degree of antenna diversity can be provided for some types of communication (e.g., signaling), for some types of services (e.g., voice), for some communications link characteristics (e.g., low C/I), or for some other conditions or considerations.

As used herein, antenna diversity includes transmit diversity and receive diversity. For transmit diversity, data is transmitted over multiple transmit antennas. Typically, additional processing is performed on the data transmitted from the transmit antennas to achieved the desired diversity. For example, the data transmitted from different transmit antennas may be ~~delayed or reordered in time, or coded and interleaved across the available~~ transmit antennas. Also, frequency and temporal diversity may be used in conjunction with the different transmit antennas. For receive diversity, modulated signals are received on multiple receive antennas, and diversity is achieved by simply receiving the signals via different transmission paths.

In accordance with another aspect of the invention, frequency diversity can be achieved by employing a multi-carrier modulation scheme. One such scheme that has numerous advantages is OFDM. With OFDM modulation, the overall transmission channel is essentially divided into a number of (L) parallel sub-channels that are used to transmit the same or different data. The overall transmission channel occupies the total operating bandwidth of W, and each of the sub-channels occupies a sub-band having a bandwidth of W/L and centered at a different center frequency. Each sub-channel has a bandwidth that is a portion of the total operating bandwidth. Each of the sub-channels may also be considered an independent data transmission channel that may be associated with a particular (and possibly unique) processing, coding, and modulation scheme, as described below.

The data may be partitioned and transmitted over any defined set of two or more sub-bands to provide frequency diversity. For example, the transmission to a particular subscriber unit may occur over sub-channel 1 at time slot 1, sub-channel 5 at time slot 2, sub-channel 2 at time slot 3, and so on. As another example, data for a particular subscriber unit may be

transmitted over sub-channels 1 and 2 at time slot 1 (e.g., with the same data being transmitted on both sub-channels), sub-channels 4 and 6 at time slot 2, only sub-channel 2 at time slot 3, and so on. Transmission of data over different sub-channels over time can improve the performance of a communications system experiencing frequency selective fading and channel distortion. Other benefits of OFDM modulation are described below.

In accordance with yet another aspect of the invention, temporal diversity is achieved by transmitting data at different times, which can be more easily accomplished using time division multiplexing (TDM). For data services (and possibly for voice services), data transmission occurs over time slots that may be selected to provide immunity to time dependent degradation in the communications link. Temporal diversity may also be achieved through the use of interleaving.

For example, the transmission to a particular subscriber unit may occur over time slots 1 through x, or on a subset of the possible time slots from 1 through x (e.g., time slots 1, 5, 8, and so on). The amount of data transmitted at each time slot may be variable or fixed. Transmission over multiple time slots improves the likelihood of correct data reception due to, for example, impulse noise and interference.

The combination of antenna, frequency, and temporal diversity allows the communications system of the invention to provide robust performance. Antenna, frequency, and/or temporal diversity improves the likelihood of correct reception of at least some of the transmitted data, which may then be used (e.g., through decoding) to correct for some errors that may have occurred in the other transmissions. The combination of antenna, frequency, and temporal diversity also allows the communications system to concurrently accommodate different types of services having disparate data rate, processing delay, and quality of service requirements.

The communications system of the invention can be designed and operated in a number of different communications modes, with each communications mode employing antenna, frequency, or temporal diversity, or a combination thereof. The communications modes include, for example, a diversity communications mode and a MIMO communications mode. Various combinations of the diversity and MIMO communications modes can also be supported by the communications system. Also, other communications modes can be implemented and are within the scope of the present invention.

The diversity communications mode employs transmit and/or receive diversity, frequency, or temporal diversity, or a combination thereof, and is generally used to improve the reliability of the communications link. In one implementation of the diversity communications mode, the transmitter unit selects a modulation and coding scheme (i.e., configuration) from a finite set of possible configurations, which are known to the receiver units. For example, each overhead and common channel may be associated with a particular configuration that is known to all receiver units. When using the diversity communications mode for a specific user (e.g., for a voice call or a data transmission), the mode and/or configuration may be known a priori (e.g., from a previous set up) or negotiated (e.g., via a common channel) by the receiver unit.

In the diversity communications mode, data is transmitted on one or more sub-channels, from one or more antennas, and at one or more time periods. The allocated sub-channels may be associated with the same antenna, or may be sub-channels associated with different antennas. In a common application of the diversity communications mode, which is also referred to as a "pure" diversity communications mode, data is transmitted from all available transmit antennas to the destination receiver unit. The pure diversity communications mode can be used in instances where the data rate requirements are low or when the C/I is low, or when both are true.

The MIMO communications mode employs antenna diversity at both ends of the communication link and is generally used to improve both the reliability and increase the capacity of the communications link. The MIMO communications mode may further employ frequency and/or temporal diversity in combination with the antenna diversity. The MIMO communications mode, which may also be referred to herein as the spatial communications mode, employs one or more processing modes to be described below.

The diversity communications mode generally has lower spectral efficiency than the MIMO communications mode, especially at high C/I levels. However, at low to moderate C/I values, the diversity communications mode achieves comparable efficiency and can be simpler to implement. In general, the use of the MIMO communications mode provides greater spectral efficiency when used, particularly at moderate to high C/I values. The MIMO communications mode may thus be advantageously used when the data rate requirements are moderate to high.

The communications system can be designed to concurrently support both diversity and MIMO communications modes. The communications modes can be applied in various manners and, for increased flexibility, may be applied independently on a sub-channel basis. The MIMO
5 communications mode is typically applied to specific users. However, each communications mode may be applied on each sub-channel independently, across a subset of sub-channels, across all sub-channels, or on some other basis. For example, the use of the MIMO communications mode may be applied to a specific user (e.g., a data user) and, concurrently, the use of the
10 diversity communications mode may be applied to another specific user (e.g., a voice user) on a different sub-channel. The diversity communications mode may also be applied, for example, on sub-channels experiencing higher path loss.

The communications system of the invention can also be designed to
15 support a number of processing modes. When the transmitter unit is provided with information indicative of the conditions (i.e., the "state") of the communications links, additional processing can be performed at the transmitter unit to further improve performance and increase efficiency. Full channel state information (CSI) or partial CSI may be available to the
20 transmitter unit. Full CSI includes sufficient characterization of the propagation path (i.e., amplitude and phase) between all pairs of transmit and receive antennas for each sub-band. Full CSI also includes the C/I per sub-band. The full CSI may be embodied in a set of matrices of complex gain values that are descriptive of the conditions of the transmission paths from
25 the transmit antennas to the receive antennas, as described below. Partial CSI may include, for example, the C/I of the sub-band. With full CSI or partial CSI, the transmitter unit pre-conditions the data prior to transmission to receiver unit.

In a specific implementation of the full-CSI processing mode, the
30 transmitter unit preconditions the signals presented to the transmit antennas in a way that is unique to a specific receiver unit (e.g., the preconditioning is performed for each sub-band assigned to that receiver unit). As long as the channel does not change appreciably from the time it is measured by the receiver unit and subsequently sent back to the transmitter
35 and used to precondition the transmission, the intended receiver unit can demodulate the transmission. In this implementation, a full-CSI based MIMO communication can only be demodulated by the receiver unit associated with the CSI used to precondition the transmitted signals.

In a specific implementation of the partial-CSI or no-CSI processing modes, the transmitter unit employs a common modulation and coding scheme (e.g., on each data channel transmission), which then can be (in theory) demodulated by all receiver units. In an implementation of the partial-CSI processing mode, a single receiver unit can specify its C/I, and the modulation employed on all antennas can be selected accordingly (e.g., for reliable transmission) for that receiver unit. Other receiver units can attempt to demodulate the transmission and, if they have adequate C/I, may be able to successfully recover the transmission. A common (e.g., broadcast) channel can use a no-CSI processing mode to reach all users.

The full-CSI processing is briefly described below. When the CSI is available at the transmitter unit, a simple approach is to decompose the multi-input multi-output channel into a set of independent channels. Given the channel transfer function at the transmitters, the left eigenvectors may be used to transmit different data streams. The modulation alphabet used with each eigenvector is determined by the available C/I of that mode, given by the eigenvalues. If \mathbf{H} is the $N_R \times N_T$ matrix that gives the channel response for the N_T transmitter antenna elements and N_R receiver antenna elements at a specific time, and \mathbf{x} is the N_T -vector of inputs to the channel, then the received signal can be expressed as:

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n}$$

where \mathbf{n} is an N_R -vector representing noise plus interference. The eigenvector decomposition of the Hermitian matrix formed by the product of the channel matrix with its conjugate-transpose can be expressed as:

$$\mathbf{H}^* \mathbf{H} = \mathbf{E} \mathbf{\tilde{E}} \mathbf{E}^*$$

where the symbol $*$ denotes conjugate-transpose, \mathbf{E} is the eigenvector matrix, and $\mathbf{\tilde{E}}$ is a diagonal matrix of eigenvalues, both of dimension $N_T \times N_T$. The transmitter converts a set of N_T modulation symbols \mathbf{b} using the eigenvector matrix \mathbf{E} . The transmitted modulation symbols from the N_T transmit antennas can thus be expressed as:

$$\mathbf{x} = \mathbf{E}\mathbf{b}$$

For all antennas, the pre-conditioning can thus be achieved by a matrix multiply operation expressed as:

16

$$\begin{bmatrix} x_1 \\ x_2 \\ \vdots \\ x_{N_T} \end{bmatrix} = \begin{bmatrix} e_{11} & e_{12} & \dots & e_{1N_T} \\ e_{21} & e_{22} & \dots & e_{2N_T} \\ \vdots & \vdots & \ddots & \vdots \\ e_{N_T1} & e_{N_T2} & \dots & e_{N_TN_T} \end{bmatrix} \cdot \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_{N_T} \end{bmatrix} \quad \text{Eq (1)}$$

where b_1, b_2, \dots and b_{N_T} are respectively the modulation symbols for a particular sub-channel at transmit antennas 1, 2, ... N_T , where each modulation symbol can be generated using, for example, M-PSK, M-QAM, and so on, as described below;

E = is the eigenvector matrix related to the transmission loss from transmit antennas to the receive antennas; and

x_1, x_2, \dots, x_{N_T} are the pre-conditioned modulation symbols, which can be expressed as:

$$\begin{aligned} x_1 &= b_1 \cdot e_{11} + b_2 \cdot e_{12} + \dots + b_{N_T} \cdot e_{1N_T} , \\ x_2 &= b_1 \cdot e_{21} + b_2 \cdot e_{22} + \dots + b_{N_T} \cdot e_{2N_T} , \text{ and} \end{aligned}$$

$$x_{N_T} = b_1 \cdot e_{N_T1} + b_2 \cdot e_{N_T2} + \dots + b_{N_T} \cdot e_{N_TN_T} .$$

15 Since $\mathbf{H}^* \mathbf{H}$ is Hermitian, the eigenvector matrix is unitary. Thus, if the elements of \mathbf{b} have equal power, the elements of \mathbf{x} also have equal power. The received signal may then be expressed as:

$$\mathbf{y} = \mathbf{H} \mathbf{E} \mathbf{b} + \mathbf{n} .$$

20 The receiver performs a channel-matched-filter operation, followed by multiplication by the right eigenvectors. The result of the channel-matched-filter operation is the vector \mathbf{z} , which can be expressed as:

$$\mathbf{z} = \mathbf{E}^* \mathbf{H}^* \mathbf{H} \mathbf{E} \mathbf{b} + \mathbf{E}^* \mathbf{H}^* \mathbf{n} = \tilde{\mathbf{E}} \mathbf{b} + \hat{\mathbf{n}} , \quad \text{Eq.(2)}$$

where the new noise term has covariance that can be expressed as:

$$E(\hat{\mathbf{n}} \hat{\mathbf{n}}^*) = E(\mathbf{E}^* \mathbf{H}^* \mathbf{n} \mathbf{n}^* \mathbf{H} \mathbf{E}) = \mathbf{E}^* \mathbf{H}^* \mathbf{H} \mathbf{E} = \Lambda ,$$

25 i.e., the noise components are independent with variance given by the eigenvalues. The C/I of the i -th component of \mathbf{z} is λ_i , the i -th diagonal element of $\tilde{\mathbf{E}}$.

The transmitter unit can thus select a modulation alphabet (i.e., signal constellation) for each of the eigenvectors based on the C/I that is given by the eigenvalue. Providing that the channel conditions do not change appreciably in the interval between the time the CSI is measured at the receiver and reported and used to precondition the transmission at the transmitter, the performance of the communications system will then be equivalent to that of a set of independent AWGN channels with known C/I's.

As an example, assume that the MIMO communications mode is applied to a channel data stream that is transmitted on one particular sub-channel from four transmit antennas. The channel data stream is demultiplexed into four data sub-streams, one data sub-stream for each transmit antenna. Each data sub-stream is then modulated using a particular modulation scheme (e.g., M-PSK, M-QAM, or other) selected based on the CSI for that sub-band and for that transmit antenna. ~~Four modulation sub-streams are thus generated for the four data sub-streams,~~ with each modulation sub-streams including a stream of modulation symbols. The four modulation sub-streams are then pre-conditioned using the eigenvector matrix, as expressed above in equation (1), to generate pre-conditioned modulation symbols. The four streams of pre-conditioned modulation symbols are respectively provided to the four combiners of the four transmit antennas. Each combiner combines the received pre-conditioned modulation symbols with the modulation symbols for the other sub-channels to generate a modulation symbol vector stream for the associated transmit antenna.

The full-CSI based processing is typically employed in the MIMO communications mode where parallel data streams are transmitted to a specific user on each of the channel eigenmodes for the each of the allocated sub-channels. Similar processing based on full CSI can be performed where transmission on only a subset of the available eigenmodes is accommodated in each of the allocated sub-channels(e.g., to implement beam steering). Because of the cost associated with the full-CSI processing (e.g., increased complexity at the transmitter and receiver units, increased overhead for the transmission of the CSI from the receiver unit to the transmitter unit, and so on), full-CSI processing can be applied in certain instances in the MIMO communications mode where the additional increase in performance and efficiency is justified.

In instances where full CSI is not available, less descriptive information on the transmission path (or partial CSI) may be available and can be used to pre-condition the data prior to transmission. For example, the C/I of each of the sub-channels may be available. The C/I information
5 can then be used to control the transmission from various transmit antennas to provide the required performance in the sub-channels of interest and increase system capacity.

As used herein, full-CSI based processing modes denote processing modes that use full CSI, and partial-CSI based processing modes denote
10 processing modes that use partial CSI. The full-CSI based processing modes include, for example, the full-CSI MIMO mode that utilizes full-CSI based processing in the MIMO communications mode. The partial-CSI based modes include, for example, the partial-CSI MIMO mode that utilizes partial-CSI based processing in the MIMO communications mode.

15 In instances where full-CSI or partial-CSI processing is employed to ~~allow the transmitter unit to pre-condition the data using the available~~ channel state information (e.g., the eigenmodes or C/I), feedback information from the receiver unit is required, which uses a portion of the reverse link capacity. Therefore, there is a cost associated with the full-CSI
20 ~~and the partial-CSI based processing modes. The cost should to be factored~~ into the choice of which processing mode to employ. The partial-CSI based processing mode requires less overhead and may be more efficient in some instances. The no-CSI based processing mode requires no overhead and may also be more efficient than the full-CSI based processing mode or the
25 partial-CSI based processing mode under some other circumstances.

If the transmitter unit has CSI and uses the eigenmodes representative of the characteristics of the communications links to transmit independent channel data streams, then the sub-channels allocated in this case are typically uniquely assigned to a single user. On the other hand, if
30 the modulation and coding scheme employed is common for all users (i.e. th CSI employed at the transmitter is not user-specific), then it is possible that information transmitted in this processing mode could be received and decoded by more than one user, depending on their C/I.

FIG. 2 is a diagram that graphically illustrates at least some of the
35 aspects of the communications system of the invention. FIG. 2 shows a specific example of a transmission from one of N_T transmit antennas at a transmitter unit. In FIG. 2, the horizontal axis is time and the vertical axis is frequency. In this example, the transmission channel includes 16 sub-

channels and is used to transmit a sequence of OFDM symbols, with each OFDM symbol covering all 16 sub-channels (one OFDM symbol is indicated at the top of FIG. 2 and includes all 16 sub-bands). A TDM structure is also illustrated in which the data transmission is partitioned into time slots, with each time slot having the duration of, for example, the length of one modulation symbol (i.e., each modulation symbol is used as the TDM interval).

The available sub-channels can be used to transmit signaling, voice, traffic data, and others. In the example shown in FIG. 2, the modulation symbol at time slot 1 corresponds to pilot data, which is periodically transmitted to assist the receiver units synchronize and perform channel estimation. Other techniques for distributing pilot data over time and frequency can also be used and are within the scope of the present invention. In addition, it may be advantageous to utilize a particular modulation scheme during the pilot interval if all sub-channels are employed (e.g., a PN code with a chip duration of approximately $1/W$).

Transmission of the pilot modulation symbol typically occurs at a particular frame rate, which is usually selected to be fast enough to permit accurate tracking of variations in the communications link.

The time slots not used for pilot transmissions can then be used to transmit various types of data. For example, sub-channels 1 and 2 may be reserved for the transmission of control and broadcast data to the receiver units. The data on these sub-channels is generally intended to be received by all receiver units. However, some of the messages on the control channel may be user specific, and can be encoded accordingly.

Voice data and traffic data can be transmitted in the remaining sub-channels. For the example shown in FIG. 2, sub-channel 3 at time slots 2 through 9 is used for voice call 1, sub-channel 4 at time slots 2 through 9 is used for voice call 2, sub-channel 5 at time slots 5 through 9 is used for voice call 3, and sub-channel 6 at time slots 7 through 9 is used for voice call 5.

The remaining available sub-channels and time slots may be used for transmissions of traffic data. In the example shown in FIG. 2, data 1 transmission uses sub-channels 5 through 16 at time slot 2 and sub-channels 7 through 16 at time slot 7, data 2 transmission uses sub-channels 5 through 16 at time slots 3 and 4 and sub-channels 6 through 16 at time slots 5, data 3 transmission uses sub-channels 6 through 16 at time slot 6, data 4 transmission uses sub-channels 7 through 16 at time slot 8, data 5 transmission uses sub-channels 7 through 11 at time slot 9, and data 6

transmission uses sub-channels 12 through 16 at time slot 9. Data 1 through 6 transmissions can represent transmissions of traffic data to one or more receiver units.

The communications system of the invention flexibly supports the
5 transmissions of traffic data. As shown in FIG. 2, a particular data transmission (e.g., data 2) may occur over multiple sub-channels and/or multiple time slots, and multiple data transmissions (e.g., data 5 and 6) may occur at one time slot. A data transmission (e.g., data 1) may also occur over non-contiguous time slots. The system can also be designed to support
10 multiple data transmissions on one sub-channel. For example, voice data may be multiplexed with traffic data and transmitted on a single sub-channel.

The multiplexing of the data transmissions can potentially change from OFDM symbol to symbol. Moreover, the communications mode may
15 be different from user to user (e.g., from one voice or data transmission to other). ~~For example, the voice users may use the diversity communications~~
mode, and the data users may use the MIMO communications modes. These features concept can be extended to the sub-channel level. For example, a data user may use the MIMO communications mode in sub-
20 ~~channels that have sufficient C/I and the diversity communications mode~~
in remaining sub-channels.

Antenna, frequency, and temporal diversity may be respectively achieved by transmitting data from multiple antennas, on multiple sub-channels in different sub-bands, and over multiple time slots. For example,
25 antenna diversity for a particular transmission (e.g., voice call 1) may be achieved by transmitting the (voice) data on a particular sub-channel (e.g., sub-channel 1) over two or more antennas. Frequency diversity for a particular transmission (e.g., voice call 1) may be achieved by transmitting the data on two or more sub-channels in different sub-bands (e.g., sub-
30 channels 1 and 2). A combination of antenna and frequency diversity may be obtained by transmitting data from two or more antennas and on two or more sub-channels. Temporal diversity may be achieved by transmitting data over multiple time slots. For example, as shown in FIG. 2, data 1 transmission at time slot 7 is a portion (e.g., new or repeated) of the data 1
35 transmission at time slot 2.

The same or different data may be transmitted from multiple antennas and/or on multiple sub-bands to obtain the desired diversity. For example, the data may be transmitted on: (1) one sub-channel from one

antenna, (2) one sub-channel (e.g., sub-channel 1) from multiple antennas, (3) one sub-channel from all N_T antennas, (4) a set of sub-channels (e.g., sub-channels 1 and 2) from one antenna, (5), a set of sub-channels from multiple antennas, (6) a set of sub-channels from all N_T antennas, or (7) a set of channels from a set of antennas (e.g., sub-channel 1 from antennas 1 and 2 at one time slot, sub-channels 1 and 2 from antenna 2 at another time slot, and so on). Thus, any combination of sub-channels and antennas may be used to provide antenna and frequency diversity.

In accordance with certain embodiments of the invention that provide the most flexibility and are capable of achieving high performance and efficiency, each sub-channel at each time slot for each transmit antenna may be viewed as an independent unit of transmission (i.e., a modulation symbol) that can be used to transmit any type of data such as pilot, signaling, broadcast, voice, traffic data, and others, or a combination thereof (e.g., multiplexed voice and traffic data). In such design, a voice call may be dynamically assigned different sub-channels over time.

Flexibility, performance, and efficiency are further achieved by allowing for independence among the modulation symbols, as described below. For example, each modulation symbol may be generated from a modulation scheme (e.g., M-PSK, M-QAM, and others) that results in the best use of the resource at that particular time, frequency, and space.

A number of constraints may be placed to simplify the design and implementation of the transmitter and receiver units. For example, a voice call may be assigned to a particular sub-channel for the duration of the call, or until such time as a sub-channel reassignment is performed. Also, signaling and/or broadcast data may be designated to some fixed sub-channels (e.g., sub-channel 1 for control data and sub-channel 2 for broadcast data, as shown FIG. 2) so that the receiver units know a priori which sub-channels to demodulate to receive the data.

Also, each data transmission channel or sub-channel may be restricted to a particular modulation scheme (e.g., M-PSK, M-QAM) for the duration of the transmission or until such time as a new modulation scheme is assigned. For example, in FIG. 2, voice call 1 on sub-channel 3 may use QPSK, voice call 2 on sub-channel 4 may use 16-QAM, data 1 transmission at time slot 2 may use 8-PSK, data 2 transmission at time slots 3 through 5 may use 16-QAM, and so on.

The use of TDM allows for greater flexibility in the transmission of voice data and traffic data, and various assignments of resources can be

contemplated. For example, a user can be assigned one sub-channel for each time slot or, equivalently, four sub-channels every fourth time slot, or some other allocations. TDM allows for data to be aggregated and transmitted at designated time slot(s) for improved efficiency.

5 If voice activity is implemented at the transmitter, then in the intervals where no voice is being transmitted, the transmitter may assign other users to the sub-channel so that the sub-channel efficiency is maximized. In the event that no data is available to transmit during the idle voice periods, the transmitter can decrease (or turn-off) the power
10 transmitted in the sub-channel, reducing the interference levels presented to other users in the system that are using the same sub-channel in another cell in the network. The same feature can be also extended to the overhead, control, data, and other channels.

Allocation of a small portion of the available resources over a
15 continuous time period typically results in lower delays, and may be better suited for delay sensitive services such as voice. Transmission using TDM can provide higher efficiency, at the cost of possible additional delays. The communications system of the invention can allocate resources to satisfy user requirements and achieve high efficiency and performance.

20 FIG. 3 is a block diagram of an embodiment of data processor 112 and modulator 114 of system 110 in FIG. 1. The aggregate input data stream that includes all data to be transmitted by system 110 is provided to a demultiplexer (DEMUX) 310 within data processor 112. Demultiplexer 310 demultiplexes the input data stream into a number of (K) channel data
25 stream, S_1 through S_K . Each channel data stream may correspond to, for example, a signaling channel, a broadcast channel, a voice call, or a traffic data transmission. Each channel data stream is provided to a respective encoder 312 that encodes the data using a particular encoding scheme.

The encoding may include error correction coding or error detection
30 coding, or both, used to increase the reliability of the link. More specifically, such encoding may include, for example, interleaving, convolutional coding, Turbo coding, Trellis coding, block coding (e.g., Reed-Solomon coding), cyclic redundancy check (CRC) coding, and others. Turbo encoding is described in further detail in U.S. Patent Application Serial No.
35 09/205,511, filed December 4, 1998 entitled "Turbo Code Interleaver Using Linear Congruential Sequences" and in a document entitled "The cdma2000 ITU-R RTT Candidate Submission," hereinafter referred to as the IS-2000 standard, both of which are incorporated herein by reference.

The encoding can be performed on a per channel basis, i.e., on each channel data stream, as shown in FIG. 3. However, the encoding may also be performed on the aggregate input data stream, on a number of channel data streams, on a portion of a channel data stream, across a set of antennas, across a set of sub-channels, across a set of sub-channels and antennas, across each sub-channel, on each modulation symbol, or on some other unit of time, space, and frequency. The encoded data from encoders 312a through 312k is then provided to a data processor 320 that processes the data to generate modulation symbols.

10 In one implementation, data processor 320 assigns each channel data stream to one or more sub-channels, at one or more time slots, and on one or more antennas. For example, for a channel data stream corresponding to a voice call, data processor 320 may assign one sub-channel on one antenna (if transmit diversity is not used) or multiple antennas (if transmit diversity
15 is used) for as many time slots as needed for that call. For a channel data stream corresponding to a signaling or broadcast channel, data processor 320 may assign the designated sub-channel(s) on one or more antennas, again depending on whether transmit diversity is used. Data processor 320 then assigns the remaining available resources for channel data streams
20 corresponding to data transmissions. Because of the burstiness nature of data transmissions and the greater tolerance to delays, data processor 320 can assign the available resources such that the system goals of high performance and high efficiency are achieved. The data transmissions are thus "scheduled" to achieve the system goals.

25 After assigning each channel data stream to its respective time slot(s), sub-channel(s), and antenna(s), the data in the channel data stream is modulated using multi-carrier modulation. In an embodiment, OFDM modulation is used to provide numerous advantages. In one implementation of OFDM modulation, the data in each channel data stream
30 is grouped to blocks, with each block having a particular number of data bits. The data bits in each block are then assigned to one or more sub-channels associated with that channel data stream.

The bits in each block are then demultiplexed into separate sub-channels, with each of the sub-channels conveying a potentially different
35 number of bits (i.e., based on C/I of the sub-channel and whether MIMO processing is employed). For each of these sub-channels, the bits are grouped into modulation symbols using a particular modulation scheme (e.g., M-PSK or M-QAM) associated with that sub-channel. For example,

with 16-QAM, the signal constellation is composed of 16 points in a complex plane (i.e., $a + j*b$), with each point in the complex plane conveying 4 bits of information. In the MIMO processing mode, each modulation symbol in the sub-channel represents a linear combination of modulation symbols, each of which may be selected from a different constellation.

The collection of L modulation symbols form a modulation symbol vector V of dimensionality L . Each element of the modulation symbol vector V is associated with a specific sub-channel having a unique frequency or tone on which the modulation symbols is conveyed. The collection of these L modulation symbols are all orthogonal to one another. At each time slot and for each antenna, the L modulation symbols corresponding to the L sub-channels are combined into an OFDM symbol using an inverse fast Fourier transform (IFFT). Each OFDM symbol includes data from the channel data streams assigned to the L sub-channels.

OFDM modulation is described in further detail in a paper entitled "Multicarrier Modulation for Data Transmission: An Idea Whose Time Has Come," by John A.C. Bingham, IEEE Communications Magazine, May 1990, which is incorporated herein by reference.

Data processor 320 thus receives and processes the encoded data corresponding to K channel data streams to provide N_T modulation symbol vectors, V_1 through V_{N_T} , one modulation symbol vector for each transmit antenna. In some implementations, some of the modulation symbol vectors may have duplicate information on specific sub-channels intended for different transmit antennas. The modulation symbol vectors V_1 through V_{N_T} are provided to modulators 114a through 114t, respectively.

In the embodiment shown in FIG. 3, each modulator 114 includes an IFFT 330, cycle prefix generator 332, and an upconverter 334. IFFT 330 converts the received modulation symbol vectors into their time-domain representations called OFDM symbols. IFFT 330 can be designed to perform the IFFT on any number of sub-channels (e.g., 8, 16, 32, and so on). In an embodiment, for each modulation symbol vector converted to an OFDM symbol, cycle prefix generator 332 repeats a portion of the time-domain representation of the OFDM symbol to form the transmission symbol for the specific antenna. The cyclic prefix insures that the transmission symbol retains its orthogonal properties in the presence of multipath delay spread, thereby improving performance against deleterious path effects, as described below. The implementation of IFFT 330 and cycle prefix generator 332 is known in the art and not described in detail herein.

The time-domain representations from each cycle prefix generator 332 (i.e., the transmission symbols for each antenna) are then processed by upconverter 332, converted into an analog signal, modulated to a RF frequency, and conditioned (e.g., amplified and filtered) to generate an RF modulated signal that is then transmitted from the respective antenna 116.

FIG. 3 also shows a block diagram of an embodiment of data processor 320. The encoded data for each channel data stream (i.e., the encoded data stream, X) is provided to a respective channel data processor 332. If the channel data stream is to be transmitted over multiple sub-channels and/or multiple antennas (without duplication on at least some of the transmissions), channel data processor 332 demultiplexes the channel data stream into a number of (up to $L \cdot N_T$) data sub-streams. Each data sub-stream corresponds to a transmission on a particular sub-channel at a particular antenna. In typical implementations, the number of data sub-streams is less than $L \cdot N_T$ since some of the sub-channels are used for signaling, voice, and other types of data. The data sub-streams are then processed to generate corresponding sub-streams for each of the assigned sub-channels that are then provided to combiners 334. Combiners 334 combine the modulation symbols designated for each antenna into modulation symbol vectors that are then provided as a modulation symbol vector stream. The N_T modulation symbol vector streams for the N_T antennas are then provided to the subsequent processing blocks (i.e., modulators 114).

In a design that provides the most flexibility, best performance, and highest efficiency, the modulation symbol to be transmitted at each time slot, on each sub-channel, can be individually and independently selected. This feature allows for the best use of the available resource over all three dimensions - time, frequency, and space. The number of data bits transmitted by each modulation symbol may thus differ.

FIG. 4A is a block diagram of an embodiment of a channel data processor 400 that can be used for processing one channel data stream. Channel data processor 400 can be used to implement one channel data processor 332 in FIG. 3. The transmission of a channel data stream may occur on multiple sub-channels (e.g., as for data 1 in FIG. 2) and may also occur from multiple antennas. The transmission on each sub-channel and from each antenna can represent non-duplicated data.

Within channel data processor 400, a demultiplexer 420 receives and demultiplexes the encoded data stream, X_e , into a number of sub-channel

data streams, $X_{i,1}$ through $X_{i,M}$, one sub-channel data stream for each sub-channel being used to transmit data. The data demultiplexing can be uniform or non-uniform. For example, if some information about the transmission paths is known (i.e., full CSI or partial CSI is known),
 5 demultiplexer 420 may direct more data bits to the sub-channels capable of transmitting more bps/Hz. However, if no CSI is known, demultiplexer 420 may uniformly directs approximately equal number of bits to each of the allocated sub-channels.

Each sub-channel data stream is then provided to a respective spatial
 10 division processor 430. Each spatial division processor 430 may further demultiplex the received sub-channel data stream into a number of (up to N_T) data sub-streams, one data sub-stream for each antenna used to transmit the data. Thus, after demultiplexer 420 and spatial division processor 430, the encoded data stream X_i may be demultiplexed into up to $L \cdot N_T$ data sub-
 15 streams to be transmitted on up to L sub-channels from up to N_T antennas.

~~At any particular time slot, up to N_T modulation symbols may be~~
 generated by each spatial division processor 430 and provided to N_T
 combiners 400a through 440t. For example, spatial division processor 430a
 assigned to sub-channel 1 may provide up to N_T modulation symbols for
 20 ~~sub-channel 1 of antennas 1 through N_T . Similarly, spatial division~~
 processor 430k assigned to sub-channel k may provide up to N_T symbols for
 sub-channel k of antennas 1 through N_T . Each combiner 440 receives the
 modulation symbols for the L sub-channels, combines the symbols for each
 time slot into a modulation symbol vector, and provides the modulation
 25 symbol vectors as a modulation symbol vector stream, V , to the next
 processing stage (e.g., modulator 114).

Channel data processor 400 may also be designed to provide the
 necessary processing to implement the full-CSI or partial-CSI processing
 modes described above. The CSI processing may be performed based on the
 30 available CSI information and on selected channel data streams, sub-
 channels, antennas, etc. The CSI processing may also be enabled and
 disabled selectively and dynamically. For example, the CSI processing may
 be enabled for a particular transmission and disabled for some other
 transmissions. The CSI processing may be enabled under certain conditions,
 35 for example, when the transmission link has adequate C/I.

Channel data processor 400 in FIG. 4A provides a high level of
 flexibility. However, such flexibility is typically not needed for all channel
 data streams. For example, the data for a voice call is typically transmitted

over one sub-channel for the duration of the call, or until such time as the sub-channel is reassigned. The design of the channel data processor can be greatly simplified for these channel data streams.

FIG. 4B is a block diagram of the processing that can be employed for one channel data stream such as overhead data, signaling, voice, or traffic data. A spatial division processor 450 can be used to implement one channel data processor 332 in FIG. 3 and can be used to support a channel data stream such as, for example, a voice call. A voice call is typically assigned to one sub-channel for multiple time slots (e.g., voice 1 in FIG. 2) and may be transmitted from multiple antennas. The encoded data stream, X_p , is provided to spatial division processor 450 that groups the data into blocks, with each block having a particular number of bits that are used to generate a modulation symbol. The modulation symbols from spatial division processor 450 are then provided to one or more combiners 440 associated with the one or more antennas used to transmit the channel data stream.

A specific implementation of a transmitter unit capable of generating the transmit signal shown in FIG. 2 is now described for a better understanding of the invention. At time slot 2 in FIG. 2, control data is transmitted on sub-channel 1, broadcast data is transmitted on sub-channel 2, voice calls 1 and 2 are assigned to sub-channels 3 and 4, respectively, and traffic data is transmitted on sub-channels 5 through 16. In this example, the transmitter unit is assumed to include four transmit antennas (i.e., $N_T = 4$) and four transmit signals (i.e., four RF modulated signals) are generated for the four antennas.

FIG. 5A is a block diagram of a portion of the processing units that can be used to generate the transmit signal for time slot 2 in FIG. 2. The input data stream is provided to a demultiplexer (DEMUX) 510 that demultiplexes the stream into five channel data streams, S_1 through S_5 , corresponding to control, broadcast, voice 1, voice 2, and data 1 in FIG. 2. Each channel data stream is provided to a respective encoder 512 that encodes the data using an encoding scheme selected for that stream.

In this example, channel data streams S_1 through S_3 are transmitted using transmit diversity. Thus, each of the encoded data streams X_1 through X_3 is provided to a respective channel data processor 532 that generates the modulation symbols for that stream. The modulation symbols from each of the channel data processors 532a through 532c are then provided to all four combiners 540a through 540d. Each combiner 540 receives the modulation

symbols for all 16 sub-channels designated for the antenna associated with the combiner, combines the symbols on each sub-channel at each time slot to generate a modulation symbol vector, and provides the modulation symbol vectors as a modulation symbol vector stream, V , to an associated modulator 114. As indicated in FIG. 5A, channel data stream S_1 is transmitted on sub-channel 1 from all four antennas, channel data stream S_2 is transmitted on sub-channel 2 from all four antennas, and channel data stream S_3 is transmitted on sub-channel 3 from all four antennas.

FIG. 5B is a block diagram of a portion of the processing units used to process the encoded data for channel data stream S_4 . In this example, channel data stream S_4 is transmitted using spatial diversity (and not transmit diversity as used for channel data streams S_1 through S_3). With spatial diversity, data is demultiplexed and transmitted (concurrently in each of the assigned sub-channels or over different time slots) over multiple antennas. The encoded data stream X_4 is provided to a channel data processor 532d that generates the modulation symbols for that stream. The

modulation symbols in this case are linear combinations of modulation symbols selected from symbol alphabets that correspond to each of the eigenmodes of the channel. In this example, there are four distinct eigenmodes, each of which is capable of conveying a different amount of information. As an example, suppose eigenmode 1 has a C/I that allows 64-QAM (6 bits) to be transmitted reliably, eigenmode 2 permits 16-QAM (4 bits), eigenmode 3 permits QPSK (2 bits) and eigenmode 4 permits BPSK (1 bit) to be used. Thus, the combination of all four eigenmodes allows a total of 13 information bits to be transmitted simultaneously as an effective modulation symbol on all four antennas in the same sub-channel. The effective modulation symbol for the assigned sub-channel on each antenna is a linear combination of the individual symbols associated with each eigenmode, as described by the matrix multiply given in equation (1) above.

FIG. 5C is a block diagram of a portion of the processing units used to process channel data stream S_5 . The encoded data stream X_5 is provided to a demultiplexer (DEMUX) 530 that demultiplexes the stream X_5 into twelve sub-channel data streams, $X_{5,11}$ through $X_{5,16}$, one sub-channel data stream for each of the allocated sub-channels 5 through 16. Each sub-channel data stream is then provided to a respective sub-channel data processor 536 that generates the modulation symbols for the associated sub-channel data stream. The sub-channel symbol stream from sub-channel data processors 536a through 536l are then provided to demultiplexers 538a through 538l,

respectively. Each demultiplexer 538 demultiplexes the received sub-channel symbol stream into four symbol sub-streams, with each symbol sub-stream corresponding to a particular sub-channel at a particular antenna. The four symbol sub-streams from each demultiplexer 538 are then
5 provided to the four combiners 540a through 540d.

In the embodiment described for FIG. 5C, a sub-channel data stream is processed to generate a sub-channel symbol stream that is then demultiplexed into four symbol sub-streams, one symbol sub-stream for a particular sub-channel of each antenna. This implementation is a different
10 from that described for FIG. 4A. In the embodiment described for FIG. 4A, the sub-channel data stream designated for a particular sub-channel is demultiplexed into a number of data sub-streams, one data sub-stream for each antenna, and then processed to generate the corresponding symbol sub-streams. The demultiplexing in FIG. 5C is performed after the symbol
15 modulation whereas the demultiplexing in FIG. 4A is performed before the ~~symbol modulation. Other implementations may also be used and are~~
within the scope of the present invention.

Each combination of sub-channel data processor 536 and demultiplexer 538 in FIG. 5C performs in similar manner as the
20 combination of sub-channel data processor 532d and demultiplexer 534d in FIG. 5B. The rate of each symbol sub-stream from each demultiplexer 538 is, on the average, a quarter of the rate of the symbol stream from the associated channel data processor 536.

FIG. 6 is a block diagram of an embodiment of a receiver unit 600,
25 having multiple receive antennas, which can be used to receive one or more channel data streams. One or more transmitted signals from one or more transmit antennas can be received by each of antennas 610a through 610r and routed to a respective front end processor 612. For example, receive antenna 610a may receive a number of transmitted signals from a number
30 of transmit antennas, and receive antenna 610r may similarly receive multiple transmitted signals. Each front end processor 612 conditions (e.g., filters and amplifies) the received signal, downconverts the conditioned signal to an intermediate frequency or baseband, and samples and quantizes the downconverted signal. Each front end processor 612 typically further
35 demodulates the samples associated with the specific antenna with the received pilot to generate "coherent" samples that are then provided to a respective FFT processor 614, one for each receive antenna.

Each FFT processor 614 generates transformed representations of the received samples and provides a respective stream of modulation symbol vectors. The modulation symbol vector streams from FFT processors 614a through 614r are then provided to demultiplexer and combiners 620, which
5 channelizes the stream of modulation symbol vectors from each FFT processor 614 into a number of (up to L) sub-channel symbol streams. The sub-channel symbol streams from all FFT processors 614 are then processed, based on the (e.g., diversity or MIMO) communications mode used, prior to demodulation and decoding.

10 For a channel data stream transmitted using the diversity communications mode, the sub-channel symbol streams from all antennas used for the transmission of the channel data stream are presented to a combiner that combines the redundant information across time, space, and frequency. The stream of combined modulation symbols are then provided
15 to a (diversity) channel processor 630 and demodulated accordingly.

~~For a channel data stream transmitted using the MIMO~~
communications mode, all sub-channel symbol streams used for the transmission of the channel data stream are presented to a MIMO processor that orthogonalizes the received modulation symbols in each sub-channel
20 ~~into the distinct eigenmodes. The MIMO processor performs the processing~~
described by equation (2) above and generates a number of independent symbol sub-streams corresponding to the number of eigenmodes used at the transmitter unit. For example, MIMO processor can perform multiplication of the received modulation symbols with the left eigenvectors to generate
25 post-conditioned modulation symbols, which correspond to the modulation symbols prior to the full-CSI processor at the transmitter unit. The (post-conditioned) symbol sub-streams are then provided to a (MIMO) channel processor 630 and demodulated accordingly. Thus, each channel processor 630 receives a stream of modulation symbols (for the diversity
30 communications mode) or a number of symbol sub-streams (for the MIMO communications mode). Each stream or sub-stream of modulation symbols is then provided to a respective demodulator (DEMOD) that implements a demodulation scheme (e.g., M-PSK, M-QAM, or others) that is complementary to the modulation scheme used at the transmitter unit for
35 the sub-channel being processed. For the MIMO communications mode, the demodulated data from all assigned demodulators may then be decoded independently or multiplexed into one channel data stream and then decoded, depending upon the coding and modulation method employed at

the transmitter unit. For both the diversity and MIMO communications modes, the channel data stream from channel processor 630 may then provided to a respective decoder 640 that implements a decoding scheme complementary to that used at the transmitter unit for the channel data stream. The decoded data from each decoder 540 represents an estimate of the transmitted data for that channel data stream.

FIG. 6 represents one embodiment of a receiver unit. Other designs can contemplated and are within the scope of the present invention. For example, a receiver unit may be designed with only one receive antenna, or may be designed capable of simultaneous processing multiple (e.g., voice, data) channel data streams.

As noted above, multi-carrier modulation is used in the communications system of the invention. In particular, OFDM modulation can be employed to provide a number of benefits including improved performance in a multipath environment, reduced implementation complexity (in a relative sense, for the MIMO mode of operation), and flexibility. However, other variants of multi-carrier modulation can also be used and are within the scope of the present invention.

OFDM modulation can improve system performance due to multipath delay spread or differential path delay introduced by the propagation environment between the transmitting antenna and the receiver antenna. The communications link (i.e., the RF channel) has a delay spread that may potentially be greater than the reciprocal of the system operating bandwidth, W . Because of this, a communications system employing a modulation scheme that has a transmit symbol duration of less than the delay spread will experience inter-symbol interference (ISI). The ISI distorts the received symbol and increases the likelihood of incorrect detection.

With OFDM modulation, the transmission channel (or operating bandwidth) is essentially divided into a (large) number of parallel sub-channels (or sub-bands) that are used to communicate the data. Because each of the sub-channels has a bandwidth that is typically much less than the coherence bandwidth of the communications link, ISI due to delay spread in the link is significantly reduced or eliminated using OFDM modulation. In contrast, most conventional modulation schemes (e.g., QPSK) are sensitive to ISI unless the transmission symbol rate is small compared to the delay spread of the communications link.

As noted above, cyclic prefix can be used to combat the deleterious effects of multipath. A cyclic prefix is a portion of an OFDM symbol (usually the front portion, after the IFFT) that is wrapped around to the back of the symbol. The cyclic prefix is used to retain orthogonality of the OFDM symbol, which is typically destroyed by multipath.

As an example, consider a communications system in which the channel delay spread is less than 10 μ sec. Each OFDM symbol has appended onto it a cyclic prefix that insures that the overall symbol retains its orthogonal properties in the presence of multipath delay spread. Since the cyclic prefix conveys no additional information, it is essentially overhead. To maintain good efficiency, the duration of the cyclic prefix is selected to be a small fraction of the overall transmission symbol duration. For the above example, using a 5% overhead to account for the cyclic prefix, an transmission symbol duration of 200 μ sec is adequate for a 10 μ sec maximum channel delay spread. The 200 μ sec transmission symbol duration corresponds to a bandwidth of 5 kHz for each of the sub-bands. If the overall system bandwidth is 1.2288 MHz, 250 sub-channels of approximately 5 kHz can be provided. In practice, it is convenient for the number of sub-channels to be a power of two. Thus, if the transmission symbol duration is increased to 205 μ sec and the system bandwidth is divided into $M = 256$ sub-bands, each sub-channel will have a bandwidth of 4.88 kHz.

In certain embodiments of the invention, OFDM modulation can reduce the complexity of the system. When the communications system incorporates MIMO technology, the complexity associated with the receiver unit can be significant, particularly when multipath is present. The use of OFDM modulation allows each of the sub-channels to be treated in an independent manner by the MIMO processing employed. Thus, OFDM modulation can significantly simplify the signal processing at the receiver unit when MIMO technology is used.

OFDM modulation can also afford added flexibility in sharing the system bandwidth, W , among multiple users. Specifically, the available transmission space for OFDM symbols can be shared among a group of users. For example, low rate voice users can be allocated a sub-channel or a fraction of a sub-channel in OFDM symbol, while the remaining sub-channels can be allocated to data users based on aggregate demand. In addition, overhead, broadcast, and control data can be conveyed in some of the available sub-channels or (possibly) in a portion of a sub-channel.

As described above, each sub-channel at each time slot is associated with a modulation symbol that is selected from some alphabet such as M-PSK or M-QAM. In certain embodiments, the modulation symbol in each of the L sub-channels can be selected such that the most efficient use is made of that sub-channel. For example, sub-channel 1 can be generated using QPSK, sub-channel 2 can be generate using BPSK, sub-channel 3 can be generated using 16-QAM, and so on. Thus, for each time slot, up to L modulation symbols for the L sub-channels are generated and combined to generate the modulation symbol vector for that time slot.

One or more sub-channels can be allocated to one or more users. For example, each voice user may be allocated a single sub-channel. The remaining sub-channels can be dynamically allocated to data users. In this case, the remaining sub-channels can be allocated to a single data user or divided among multiple data users. In addition, some sub-channels can be reserved for transmitting overhead, broadcast, and control data. In certain embodiments of the invention, it may be desirable to change the sub-channel assignment from (possibly) modulation symbol to symbol in a pseudo-random manner to increase diversity and provide some interference averaging.

In a CDMA system, the transmit power on each reverse link transmission is controlled such that the required frame error rate (FER) is achieved at the base station at the minimal transmit power, thereby minimizing interference to other users in the system. On the forward link of the CDMA system, the transmit power is also adjusted to increase system capacity.

In the communications system of the invention, the transmit power on the forward and reverse links can be controlled to minimize interference and maximize system capacity. Power control can be achieved in various manners. For example, power control can be performed on each channel data stream, on each sub-channel, on each antenna, or on some other unit of measurements. When operating in the diversity communications mode, if the path loss from a particular antenna is great, transmission from this antenna can be reduced or muted since little may be gained at the receiver unit. Similarly, if transmission occurs over multiple sub-channels, less power may be transmitted on the sub-channel(s) experiencing the most path loss.

In an implementation, power control can be achieved with a feedback mechanism similar to that used in the CDMA system. Power control

information can be sent periodically or autonomously from the receiver unit to the transmitter unit to direct the transmitter unit to increase or decrease its transmit power. The power control bits may be generated based on, for example, the BER or FER at the receiver unit.

5 FIG. 7 shows plots that illustrate the spectral efficiency associated with some of the communications modes of the communications system of the invention. In FIG. 7, the number of bits per modulation symbol for a given bit error rate is given as a function of C/I for a number of system configurations. The notation $N_T \times N_R$ denotes the dimensionality of the configuration, with N_T = number of transmit antennas and N_R = number of
10 receive antennas. Two diversity configurations, namely 1x2 and 1x4, and four MIMO configurations, namely 2x2, 2x4, 4x4, and 8x4, are simulated and the results are provided in FIG. 7.

As shown in the plots, the number of bits per symbol for a given BER
15 ranges from less than 1 bps/Hz to almost 20 bps/Hz. At low values of C/I, ~~the spectral efficiency of the diversity communications mode and MIMO~~
~~communications mode is similar, and the improvement in efficiency is less~~
~~noticeable. However, at higher values of C/I, the increase in spectral~~
~~efficiency with the use of the MIMO communications mode becomes more~~
20 ~~dramatic. In certain MIMO configurations and for certain conditions, the~~
instantaneous improvement can reach up to 20 times.

From these plots, it can be observed that spectral efficiency generally
increases as the number of transmit and receive antennas increases. The
improvement is also generally limited to the lower of N_T and N_R . For
25 example, the diversity configurations, 1x2 and 1x4, both asymptotically reach
approximately 6 bps/Hz.

In examining the various data rates achievable, the spectral efficiency
values given in FIG. 7 can be applied to the results on a sub-channel basis to
obtain the range of data rates possible for the sub-channel. As an example,
30 for a subscriber unit operating at a C/I of 5 dB, the spectral efficiency
achievable for this subscriber unit is between 1 bps/Hz and 2.25 bps/Hz,
depending on the communications mode employed. Thus, in a 5 kHz sub-
channel, this subscriber unit can sustain a peak data rate in the range of 5
kbps to 10.5 kbps. If the C/I is 10 dB, the same subscriber unit can sustain
35 peak data rates in the range of 10.5 kbps to 25 kbps per sub-channel. With
256 sub-channels available, the peak sustained data rate for a subscriber unit
operating at 10 dB C/I is then 6.4 Mbps. Thus, given the data rate
requirements of the subscriber unit and the operating C/I for the subscriber

unit, the system can allocate the necessary number of sub-channels to meet the requirements. In the case of data services, the number of sub-channels allocated per time slot may vary depending on, for example, other traffic loading.

- 5 The reverse link of the communications system can be designed similar in structure to the forward link. However, instead of broadcast and common control channels, there may be random access channels defined in specific sub-channels or in specific modulation symbol positions of the frame, or both. These may be used by some or all subscriber units to send
10 short requests (e.g., registration, request for resources, and so on) to the central station. In the common access channels, the subscriber units may employ common modulation and coding. The remaining channels may be allocated to separate users as in the forward link. In an embodiment, allocation and de-allocation of resources (on both the forward and reverse
15 links) are controlled by the system and communicated on the control channel in the forward link.
-

- One design consideration for on the reverse link is the maximum differential propagation delay between the closest subscriber unit and the furthest subscriber unit. In systems where this delay is small relative to the
20 cyclic prefix duration, it may not be necessary to perform correction at the transmitter unit. However, in systems in which the delay is significant, the cyclic prefix can be extended to account for the incremental delay. In some instances, it may be possible to make a reasonable estimate of the round trip delay and correct the time of transmit so that the symbol arrives at the
25 central station at the correct instant. Usually there is some residual error, so the cyclic prefix may also further be extended to accommodate this residual error.

- In the communications system, some subscriber units in the coverage area may be able to receive signals from more than one central station. If
30 the information transmitted by multiple central stations is redundant on two or more sub-channels and/or from two or more antennas, the received signals can be combined and demodulated by the subscriber unit using a diversity-combining scheme. If the cyclic prefix employed is sufficient to handle the differential propagation delay between the earliest and latest
35 arrival, the signals can be (optimally) combined in the receiver and demodulated correctly. This diversity reception is well known in broadcast applications of OFDM. When the sub-channels are allocated to specific subscriber units, it is possible for the same information on a specific sub-

channel to be transmitted from a number of central stations to a specific subscriber unit. This concept is similar to the soft handoff used in CDMA systems.

As shown above, the transmitter unit and receiver unit are each
5 implemented with various processing units that include various types of data processor, encoders, IFFTs, FFTs, demultiplexers, combiners, and so on. These processing units can be implemented in various manners such as an application specific integrated circuit (ASIC), a digital signal processor, a microcontroller, a microprocessor, or other electronic circuits designed to
10 perform the functions described herein. Also, the processing units can be implemented with a general-purpose processor or a specially designed processor operated to execute instruction codes that achieve the functions described herein. Thus, the processing units described herein can be implemented using hardware, software, or a combination thereof.

15 The foregoing description of the preferred embodiments is provided to enable any person skilled in the art to make or use the present invention.

Various modifications to these embodiments will be readily apparent to those skilled in the art, and the generic principles defined herein may be applied to other embodiments without the use of the inventive faculty.

20 Thus, the present invention is not intended to be limited to the embodiments shown herein but is to be accorded the widest scope consistent with the principles and novel features disclosed herein.

WHAT IS CLAIMED IS:

CLAIMS

1. A transmitter unit in a communications system configurable to
2 provide antenna, frequency, or temporal diversity, or a combination thereof,
for transmitted signals, comprising:
4 a system data processor operative to receive and partition an input
data stream into a plurality of channel data streams and to process the
6 plurality of channel data streams to generate one or more modulation
symbol vector streams, wherein each modulation symbol vector stream
8 comprises a sequence of modulation symbol vectors representative of the
data in one or more channel data streams, and wherein each modulation
10 symbol vector comprises a plurality of modulation symbols and is generated
and transmitted in a manner to provide antenna, frequency, or temporal
12 diversity, or a combination thereof;

at least one modulator coupled to the system data processor, the at
14 ~~least one modulator operative to receive and modulate a respective~~
modulation symbol vector stream to provide a modulated signal; and
16 at least one antenna coupled to the at least one modulator, the at least
one antenna operative to receive and transmit a respective modulated
18 signal.

2. The transmitter unit of claim 1, wherein the system data processor
2 includes
at least one channel data processor, each channel data processor
4 operative to receive and process a respective channel data stream to generate
a stream of modulation symbols.

3. The transmitter unit of claim 2, wherein the system data processor
2 further includes
at least one encoder, each encoder operative to receive and encode a
4 respective channel data stream to generate an encoded data stream, and
wherein each channel data processor is operative to receive and
6 process a respective encoded data stream.

4. The transmitter unit of claim 2, wherein the system data processor
2 further includes
at least one demultiplexer, each demultiplexer coupled to a respective
4 channel data processor and operative to receive and demultiplex the stream

of modulation symbols into one or more symbol sub-streams, one symbol
6 sub-stream for each antenna.

5. The transmitter unit of claim 2, wherein the system data processor
2 further includes

at least one combiner, one combiner for each antenna, each combiner
4 coupled to the at least one channel data processor and operative to receive
and selectively combine at least one stream of modulation symbols from the
6 at least one channel data processor to generate a respective modulation
symbol vector stream.

6. The transmitter unit of claim 1, wherein each modulator includes
2 an inverse Fourier transform operative to receive a respective
modulation symbol vector stream and generate a time-domain
4 representation of the modulation symbol vector stream.

7. The transmitter unit of claim 6, wherein each modulator further
2 includes
a cyclic prefix generator coupled to the inverse Fourier transform and
4 operative to repeat a portion of the time-domain representation of each
modulation symbol vector.

8. The transmitter unit of claim 1, wherein the system data processor
2 is operative to modulate the plurality of channel data streams using multi-
carrier modulation to generate the one or more symbol vector streams.

9. The transmitter unit of claim 8, wherein the multi-carrier
2 modulation is orthogonal frequency division multiplexing (OFDM)
modulation.

10. The transmitter unit of claim 8, wherein the multi-carrier
2 modulation partitions a total operating bandwidth of the communications
system into a plurality of (L) sub-bands, wherein each sub-band is associated
4 with a different center frequency and corresponds to one sub-channel.

11. The transmitter unit of claim 8, wherein data on each channel
2 data stream is modulated with a particular modulation scheme selected
from a set that includes M-PSK and M-QAM.

12. The transmitter unit of claim 8, wherein data to be transmitted on
2 each sub-channel is modulated with a particular modulation scheme
selected from a set that includes M-PSK and M-QAM.

13. The transmitter unit of claim 10, wherein L is 64 or greater.

14. The transmitter unit of claim 10, wherein L is 256 or greater.

15. The transmitter unit of claim 1, wherein the modulation symbol
2 vectors in the modulation symbol vector stream are orthogonal frequency
division multiplexing (OFDM) symbols.

16. The transmitter unit of claim 1, wherein at least one channel data
2 stream is processed using a diversity communications mode characterized
by transmission of each of the at least one channel data stream on one or
4 more sub-channels, from one or more antennas, or at one or more time
periods, or a combination thereof, to improve the reliability of the
6 transmission.

17. The transmitter unit of claim 1, wherein use of the diversity
2 communications mode is based, in part, on a quality of one or more
communications links used for a particular channel data stream
4 transmission.

18. The transmitter unit of claim 1, wherein at least one channel data
2 stream is processed using a MIMO communications mode characterized by
transmission of each of the at least one channel data stream using a plurality
4 of transmit antennas and reception of the transmission using a plurality of
receive antennas to improve the reliability of the transmission and increase
6 link capacity.

19. The transmitter unit of claim 1, wherein at least one channel data
2 stream is processed using a diversity communications mode and at least one
other channel data stream is processed using a MIMO communications
4 mode, wherein the diversity communications mode is characterized by
transmission of a channel data stream on one or more sub-channels, from
6 one or more antennas, or at one or more time periods, or a combination

thereof, to improve the reliability of the transmission, and wherein the
8 MIMO communications mode characterized by transmission of a channel
data stream using a plurality of transmit antennas and reception of the
10 transmission using a plurality of receive antennas to improve the reliability
of the transmission and increase link capacity.

20. The transmitter unit of claim 1, wherein the system data
2 processor is further operative to pre-condition the modulation symbols in
accordance with channel state information (CSI) descriptive of
4 characteristics of one or more communications links used to transmit the
one or more modulated signals.

21. The transmitter unit of claim 20, wherein the CSI includes carrier-
2 to-noise-plus-interference ratio (C/I) values for the one or more
communications links.

22. The transmitter unit of claim 20, wherein the CSI is defined by a
2 matrix corresponding to the one or more communications links.

23. The transmitter unit of claim 1, wherein at least one channel data
2 stream is transmitted over two or more antennas, concurrently or at
different times, to provide antenna diversity.

24. The transmitter unit of claim 1, wherein at least a portion of at
2 least one channel data stream is redundantly transmitted over two or more
antennas to provide transmit diversity.

25. The transmitter unit of claim 1, wherein at least a portion of at
2 least one channel data stream is transmitted over two or more time periods
to provide temporal diversity.

26. The transmitter unit of claim 10, wherein at least a portion of at
2 least one channel data stream is transmitted on two or more sub-bands to
provide frequency diversity.

27. The transmitter unit of claim 1, wherein the plurality of channel
2 data streams are transmitted in time division multiplexed (TDM) time slots.

28. The transmitter unit of claim 27, wherein the each time slot has a
2 duration that is related to a length of one modulation symbol.

29. The transmitter unit of claim 1, and configurable to concurrently
2 transmit voice data and traffic data.

30. The transmitter unit of claim 29, wherein voice data for a
2 particular voice call is allocated a portion of an available transmission
resource for the duration of the voice call.

31. The transmitter unit of claim 29, wherein voice data for a
2 particular voice call is assigned a particular sub-channel for the duration of
the voice call.

32. The transmitter unit of claim 1, wherein pilot data is time
2 division multiplexed with other data and is transmit periodically.

33. A communications system configurable to provide antenna,
2 frequency, or temporal diversity, or a combination thereof, for transmitted
signals, comprising:
4 a system data processor operative to receive and partition an input
data stream into a plurality of channel data streams and to encode and
6 modulate the plurality of channel data streams using orthogonal frequency
division multiplexing (OFDM) modulation to generate one or more OFDM
8 symbol streams, wherein each OFDM symbol stream comprises a sequence
of OFDM symbols representative of data from one or more channel data
10 streams, and wherein each OFDM symbols occupies one time slot and is
selected and subsequently transmitted in a manner to provide antenna,
12 frequency, or temporal diversity, or a combination thereof;
at least one modulator coupled to the data processor, each modulator
14 operative to receive and modulate a respective OFDM symbol stream to
provide a modulated signal; and
16 at least one antenna coupled to the at least one modulator, each
antenna operative to receive and transmit a respective modulated signal.

34. A receiver unit comprising:
2 at least one antenna, each antenna operative to receive at least one
modulated signal;

4 at least one front end processor coupled to the at least one antenna,
each front end processor operative to process a received signal from a
6 respective antenna to generate samples;
at least one Fourier transform coupled to the at least one front end
8 processor, each Fourier transform operative to receive samples from a
respective front end processor and generate transformed representations of
10 the samples;
a processor coupled to the at least one Fourier transform and
12 operative to process the transformed representations to generate at least one
symbol stream, each symbol stream corresponding to a particular
14 transmission being processed; and
at least one demodulator coupled to the demultiplexer, each
16 demodulator operative to receive and demodulate a respective symbol
stream to generate demodulated data,
18 wherein the modulated signals are generated and transmitted in a
~~manner to provide antenna, frequency, or temporal diversity, or a~~
20 combination thereof.

35. The receiver unit claim 34, further comprising:

~~2~~ at least one decoder coupled to the at least one demodulator, each
decoder operative to receive and decode respective demodulated data to
4 generate decoded data corresponding to the particular transmission being
processed.

36. The receiver unit claim 34, wherein the receiver unit is operative
2 to determine characteristics of at least one communications link used to
receive the at least one modulated signal and to send information
4 descriptive of the determined link characteristics.

37. The receiver unit claim 36, wherein the sent information
2 comprises signal-to-noise-plus-interference ratio (C/I) values for the at least
one communications link.

38. The receiver unit claim 36, wherein the sent information
2 comprises a matrix corresponding to the at least one communications link.

39. A receiver unit comprising:

2 at least one antenna operative to receive at least one modulated
signal that have been previously generated and transmitted by
4 partitioning an input data stream into a plurality of channel
data streams,
6 encoding the plurality of channel data streams with at least one
encoding scheme,
8 modulating the encoded data with at least one modulation
scheme to generate modulation symbols,
10 selectively combining sets of modulation symbols into
modulation symbol vectors, and
12 selectively combining modulation symbol vectors to form at
least one modulation symbol vector stream,
14 wherein the modulation symbol vectors are generated and
transmitted in a manner to provide antenna, frequency, or temporal
16 diversity, or a combination thereof; and
~~at least one processing unit coupled to the at least one antenna and~~
18 operative to process at least one received signal to generate output data.

40. A method for generating and transmitting at least one modulated
2 signal, comprising:
receiving an input data stream;
4 partitioning the input data stream into a plurality of channel data
streams;
6 encoding the plurality of channel data streams with at least one
encoding scheme;
8 modulating the encoded data with at least one modulation scheme to
generate modulation symbols;
10 selectively combining sets of modulation symbols into modulation
symbol vectors;
12 selectively combining modulation symbols to form at least one
modulation symbol vector stream; and
14 transmitting the at least one modulation symbol vector stream from
at least one antenna,
16 wherein the modulation symbol vectors are generated and
transmitted in a manner to provide antenna, frequency, or temporal
18 diversity, or a combination thereof.

41. The method claim 40, further comprising:

44

- 2 demultiplexing each channel data stream into at least one sub-
channel data stream, one sub-channel data stream for each of the at least one
4 antenna used for transmission of the channel data stream.

42. The method claim 41, further comprising:

- 2 demultiplexing each sub-channel data stream into at least one data
sub-stream, one data sub-stream for each sub-band used for transmission of
4 the channel data stream.

43. The method claim 42, wherein the modulating is performed

- 2 using a particular modulation scheme for each channel data stream, or each
sub-channel data stream, or each data sub-stream, or each combination
4 thereof.

44. The method claim 40, further comprising:

- 2 ~~pre-processing modulation symbols corresponding to a particular~~
channel data stream in accordance with full or partial channel state
4 information.

1/10

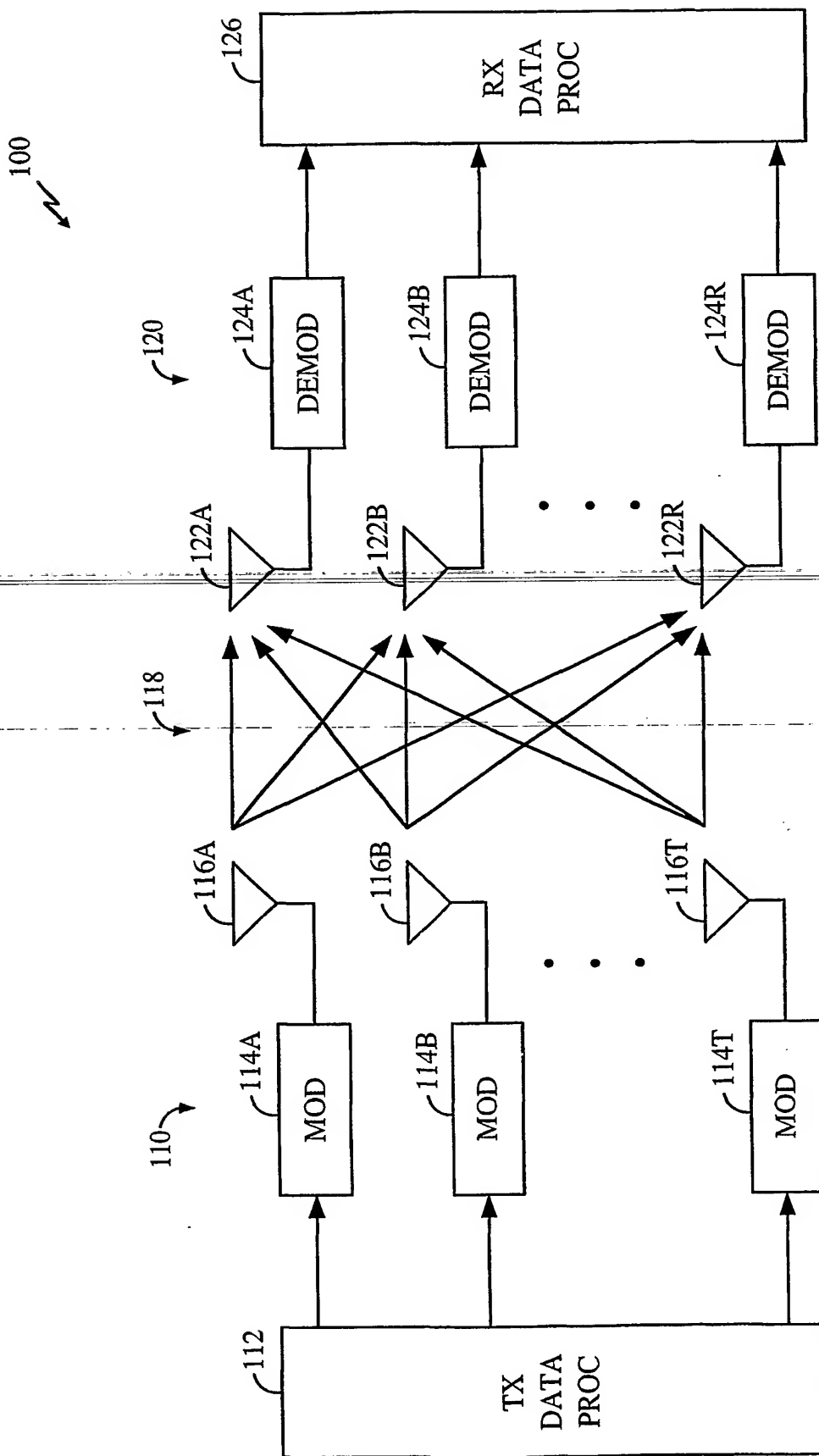


FIG. 1A

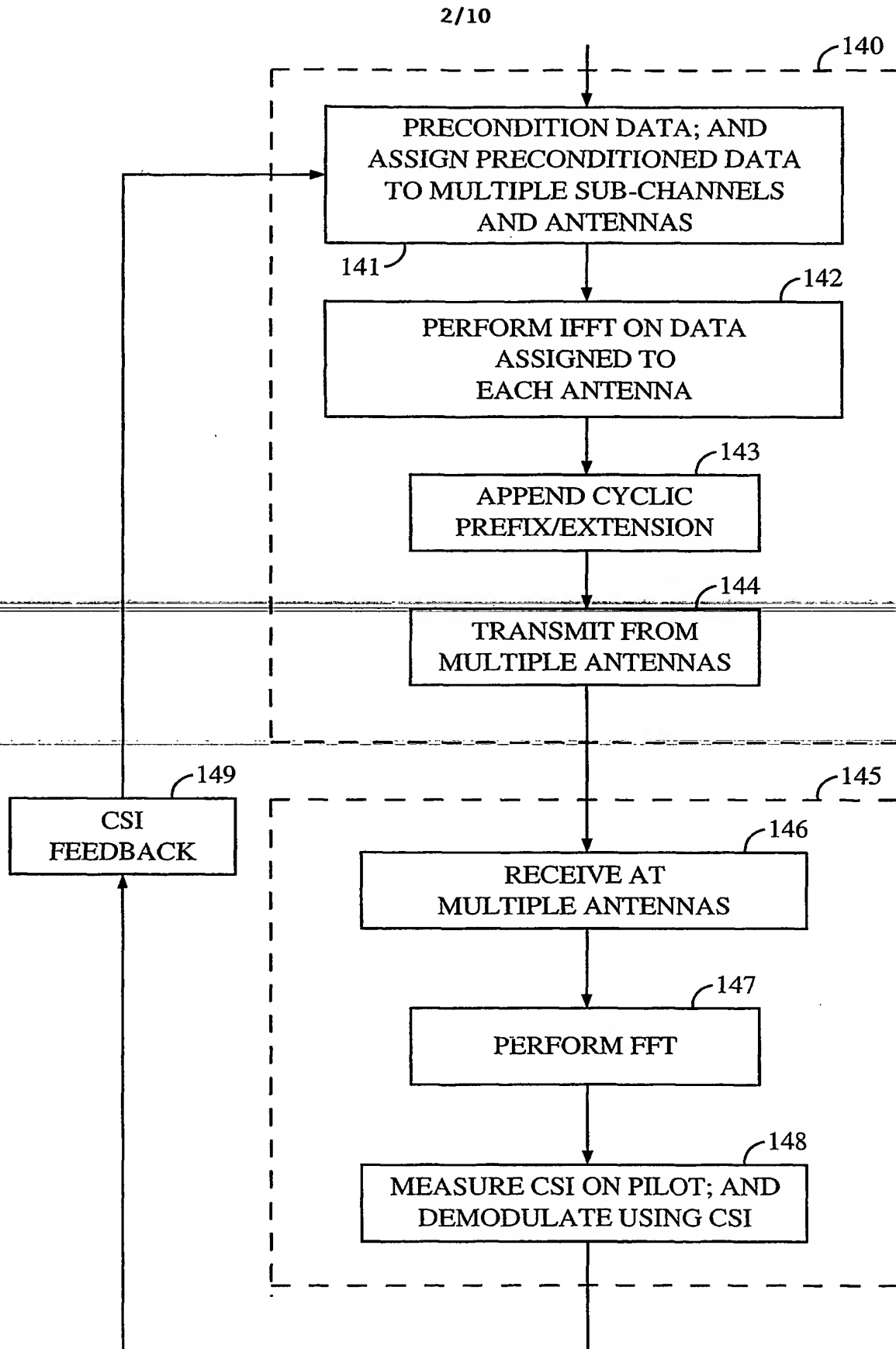


FIG. 1B

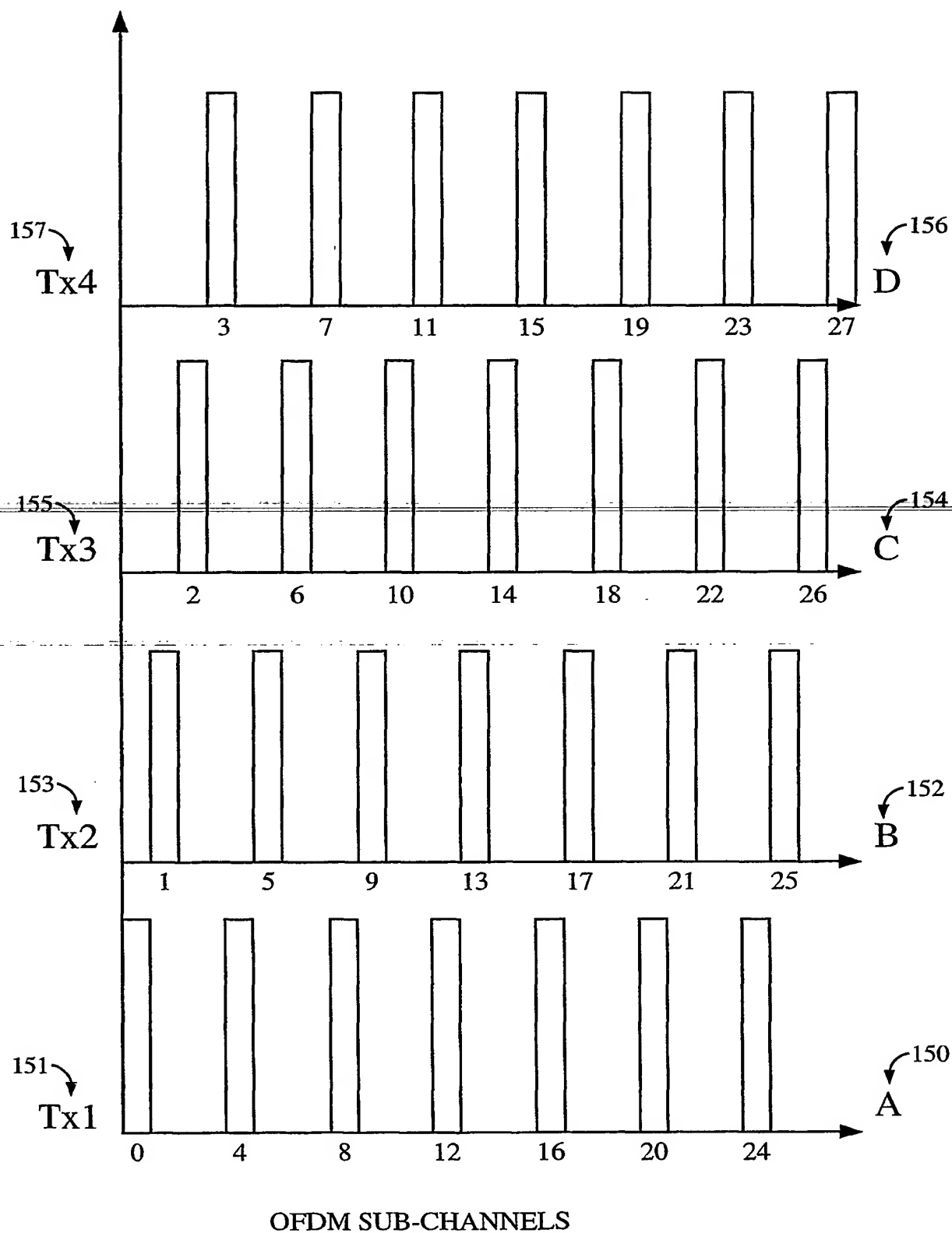


FIG. 1C

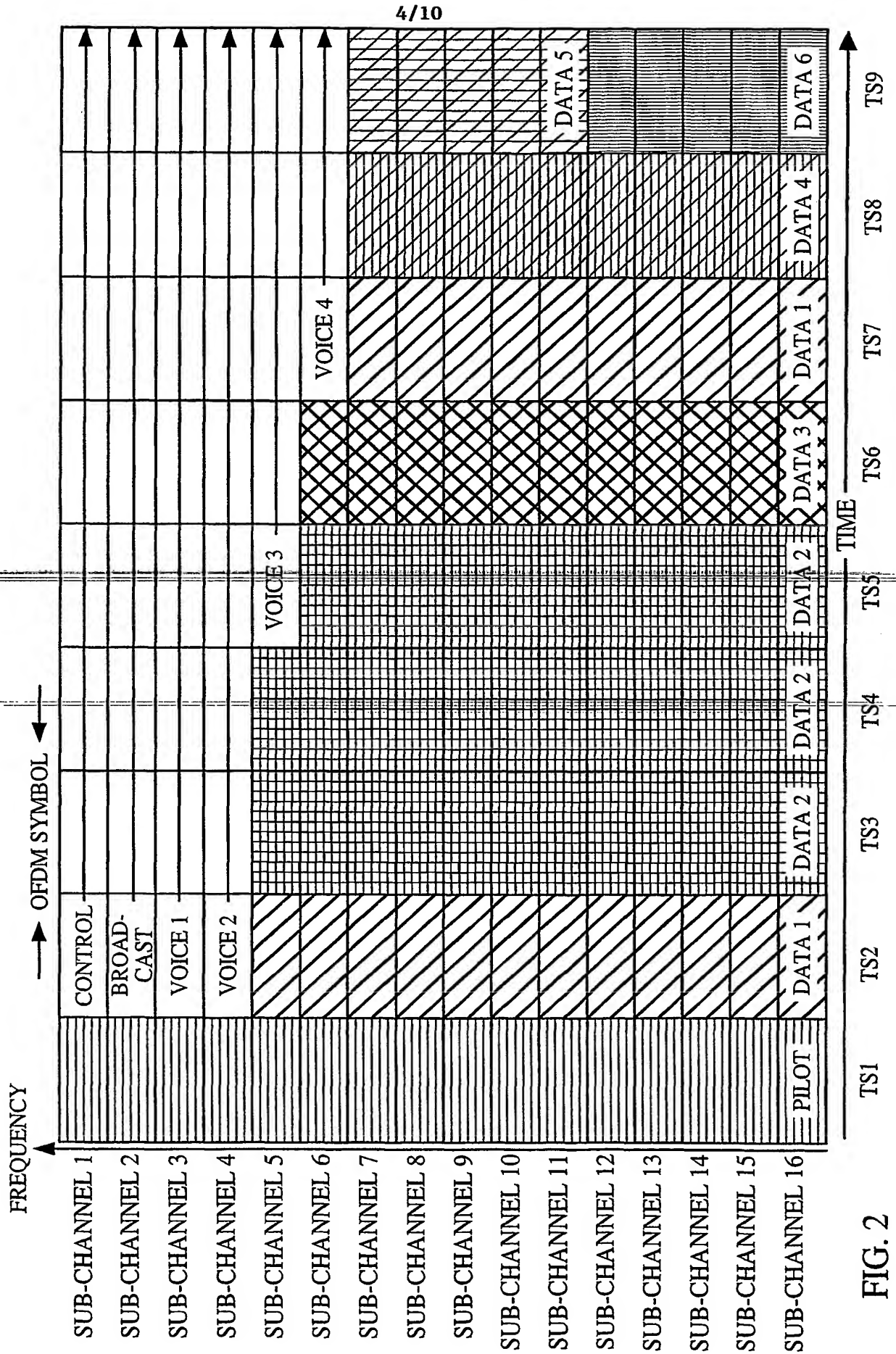
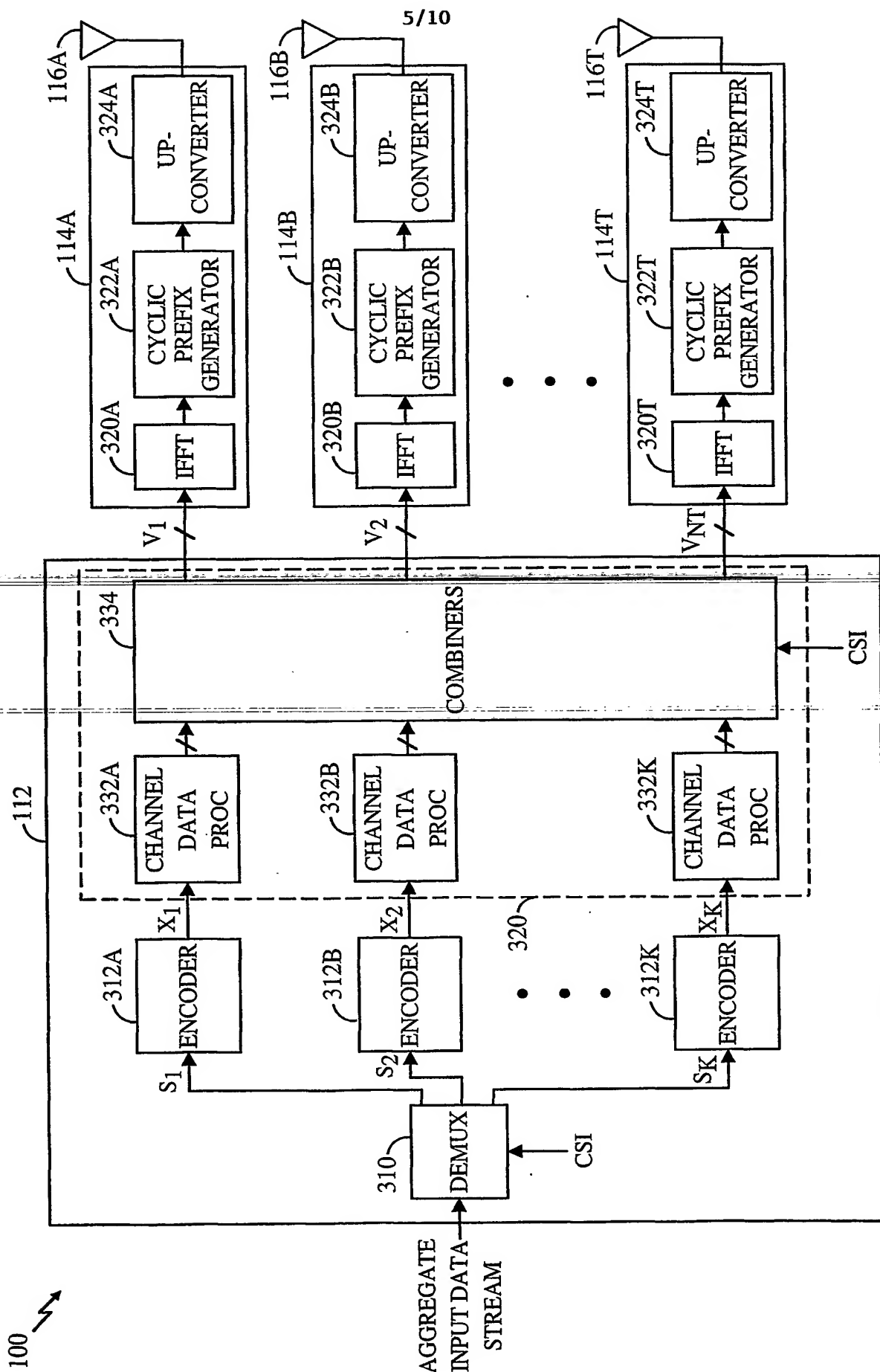


FIG. 2



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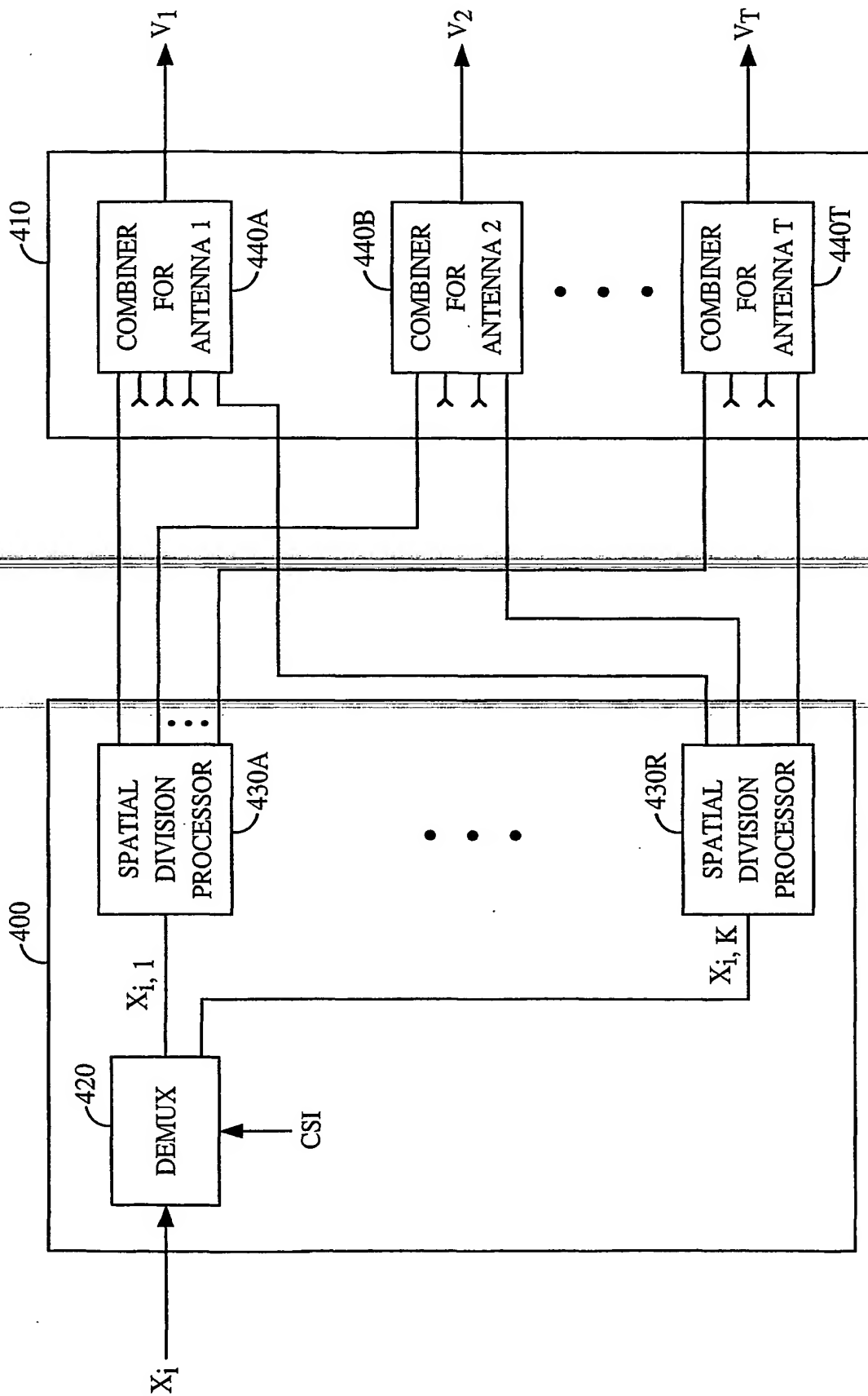


FIG. 4A

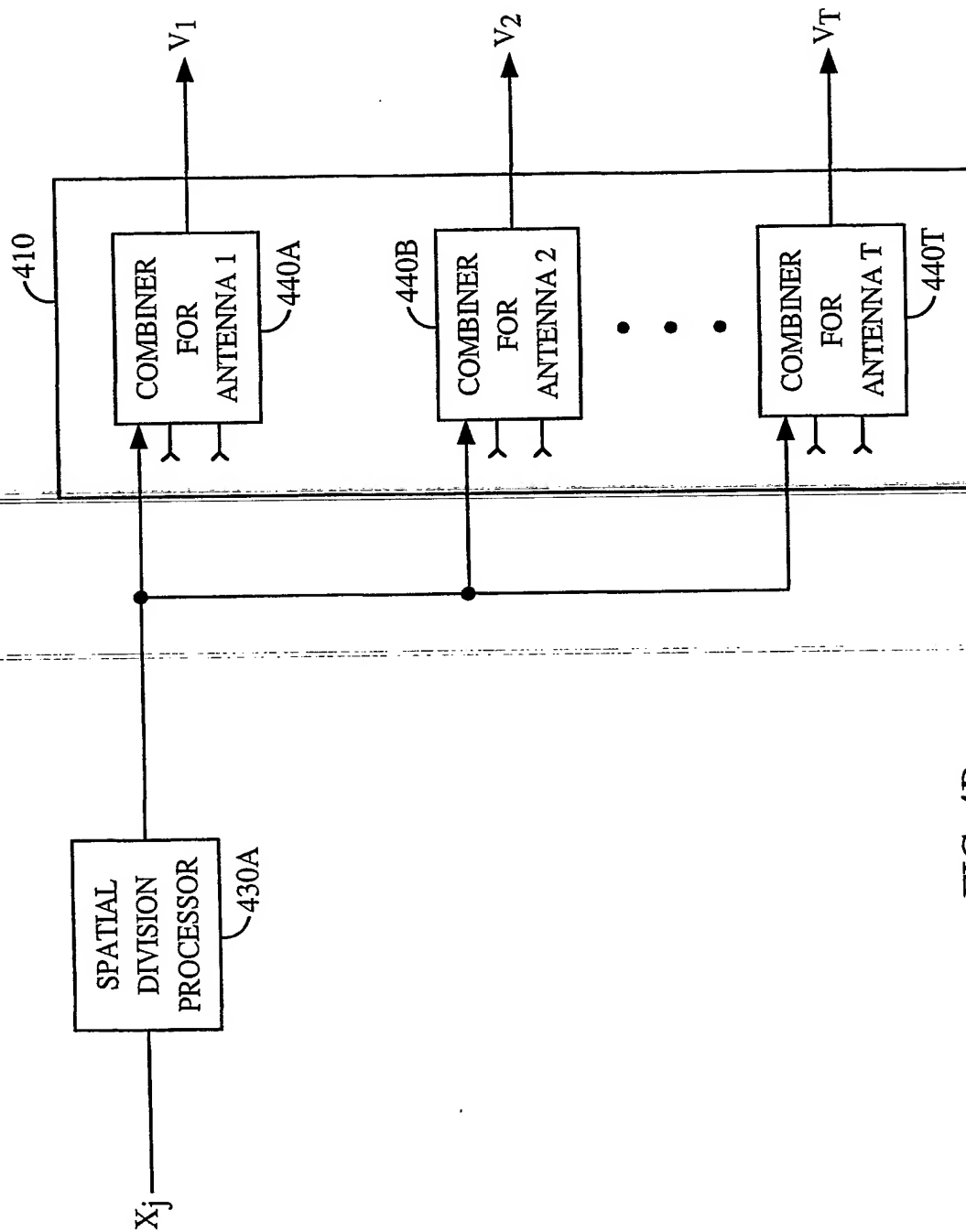


FIG. 4B

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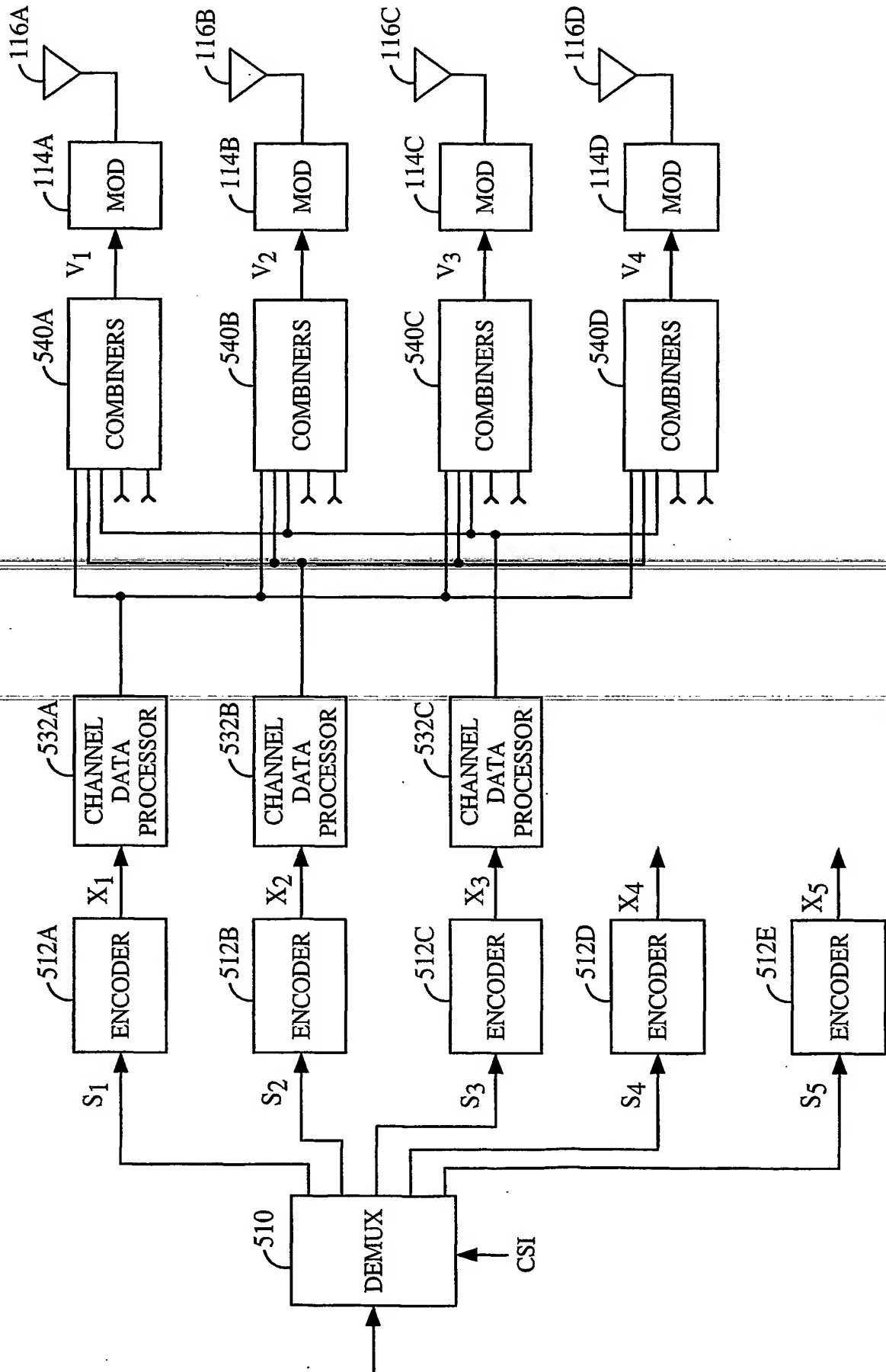


FIG. 5A

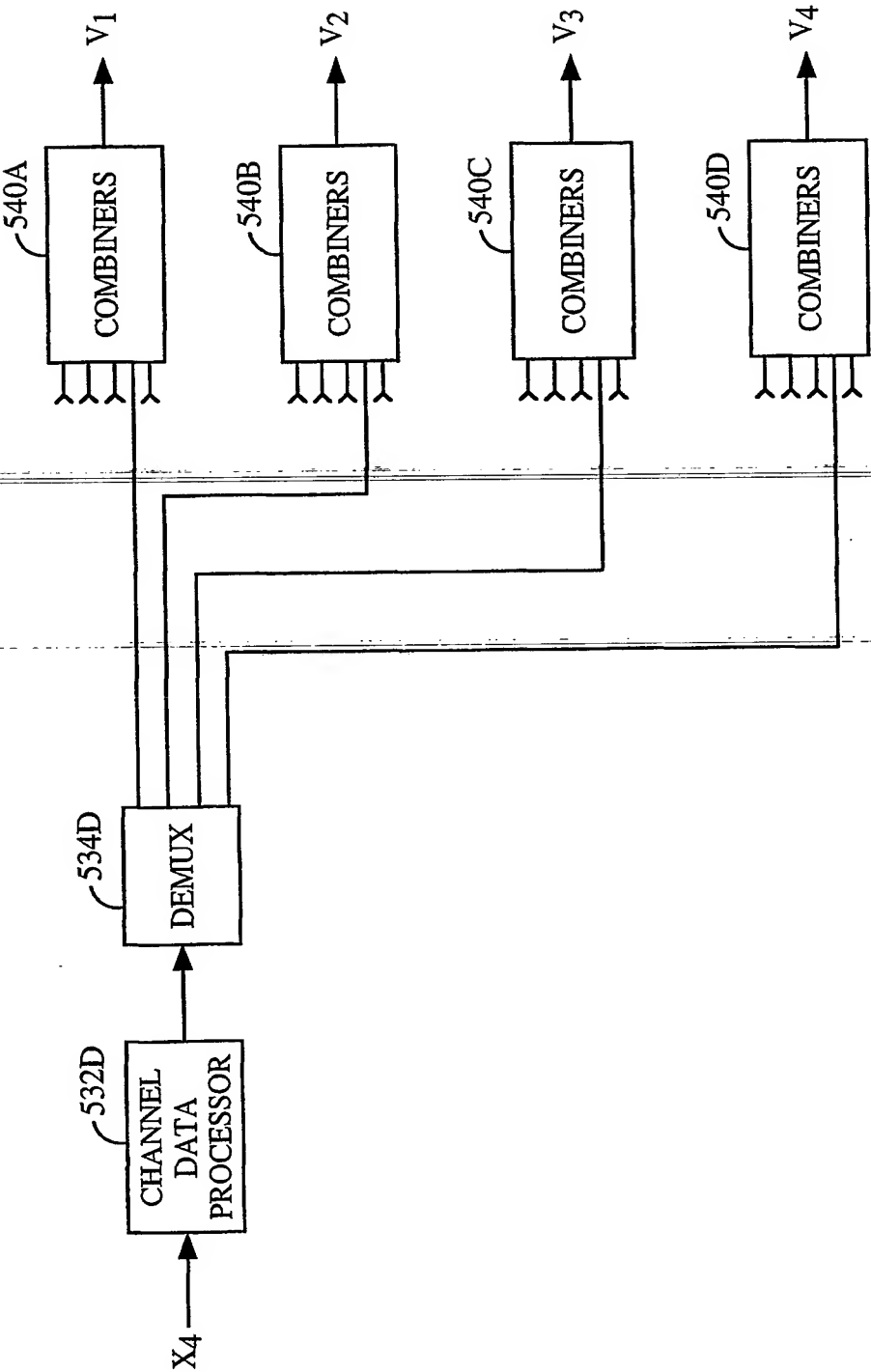


FIG. 5B

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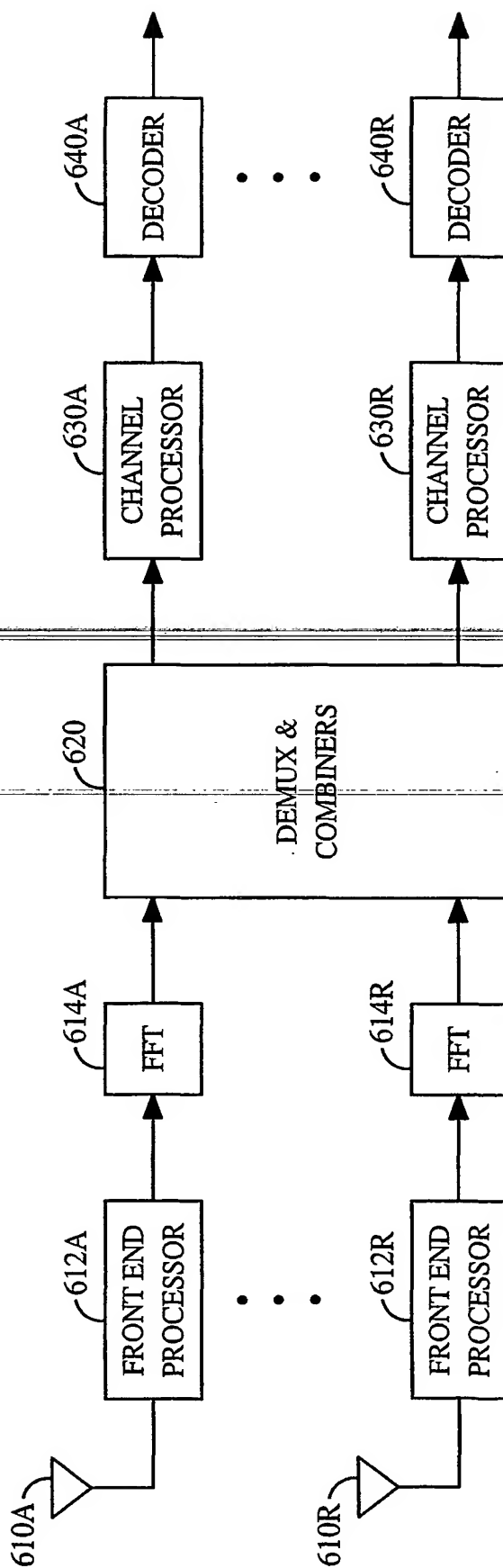


FIG. 6

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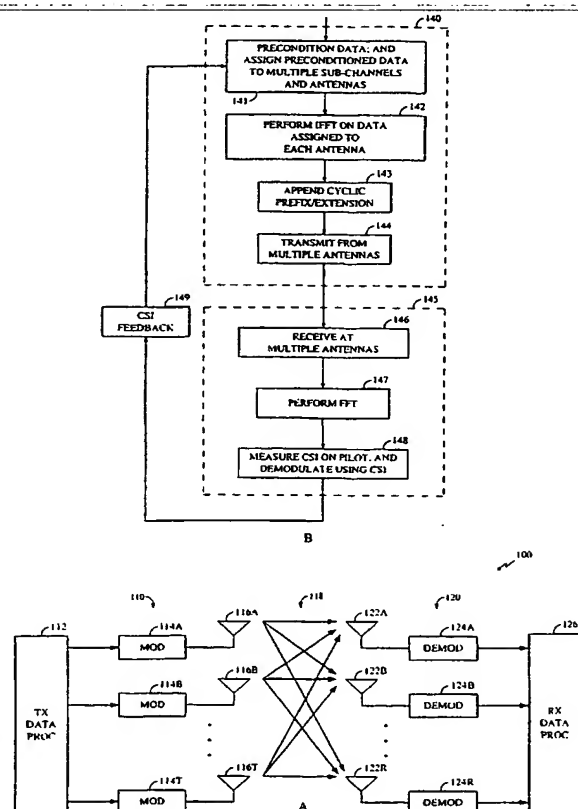
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5775 Morehouse Drive, San Diego, CA 92121-1714 (US).(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE,(72) Inventors: **WALTON, Jay, R.**; 7 Ledgewood Drive, Westford, MA 01886 (US). **WALLACE, Mark**; 4 Madel Lane,

[Continued on next page]

(54) Title: HIGH EFFICIENCY, HIGH PERFORMANCE COMMUNICATIONS SYSTEM EMPLOYING MULTI-CARRIER MODULATION



(57) Abstract: Transmitter and receiver units for use in a communications system and configurable to provide antenna, frequency, or temporal diversity, or a combination thereof, for transmitted signals. The transmitter unit includes a system data processor, one or more modulators, and one or more antennas. The system data processor receives and partitions an input data stream into a number of channel data streams and further processes the channel data streams to generate one or more modulation symbol vector streams. Each modulation symbol vector stream includes a sequence of modulation symbol vectors representative of data in one or more channel data streams. Each modulator receives and modulates a respective modulation symbol vector stream to provide an RF modulated signal, and each antenna receives and transmits a respective RF modulated signal. Each modulator may include an inverse (fast) Fourier transform (IFFT) and a cyclic prefix generator. The IFFT generates time-domain representations of the modulation symbol vectors, and the cyclic prefix generator repeats a portion of the time-domain representation of each modulation symbol vector. The channel data streams are modulated using multi-carrier modulation, e.g., OFDM modulation. Time division multiplexing (TDM) may also be used to increase flexibility.

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INTERNATIONAL SEARCH REPORT

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Minimum documentation searched (classification system followed by classification symbols)

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Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

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In International Application No

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